A PERFORMANCE STUDY OF CERAMIC CANDLE FILTERS IN KENYA INCLUDING TESTS FOR COLIPHAGE REMOVAL

By

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B.S. Chemistry
University of North Carolina at Chapel Hill, 2004

Submitted to the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of

MASTER OF ENGINEERING IN CIVIL AND ENVIRONMENTAL ENGINEERING
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 2005

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ABSTRACT

Approximately 80% of all diseases in the developing world are caused by contaminated water (GDRC, 1999). In response to this crisis, decentralized point-of-use systems, such as ceramic candle filters, have emerged as viable options for improving water quality at the household level. This thesis evaluates the performance of five brands of ceramic candle filters that are locally available in the developing nation of Kenya: the AquaMaster (Piedra candle), Doulton Super Sterasyl, Stefani São João, Pelikan, and Pozzani candles. Filters were evaluated based on turbidity removal, flow rate, total coliform and *E. coli* removal, and cost. The Pelikan filters were also subjected to tests for viral removal using MS2-coliphages.

Results from studies indicated that the Pelikan filters were the most effective at removing turbidity from Charles River water (97% reduction). Turbidity removal by other filters ranged from 88%-94%. Results from studies utilizing more turbid Nairobi water showed filters to reduce turbidity by 97%-99%. Results from flow rate studies performed at MIT revealed the Doulton Super Sterasyl to possess a significantly greater flow rate (0.55 L/hr) than the other brands. The flow rates of the other filters ranged from 0.14-0.26 L/hr. Filter tests utilizing the more turbid Nairobi water showed flow rates of 0.09-0.24 L/hr. Results from coliform removal studies performed at MIT showed the AquaMaster (Piedra candle), Doulton Super Sterasyl, and Pelikan filters to remove significantly more total coliform and *E. coli* than the Pozzani filters. Percent removal by all filters tested at MIT ranged from 92%-<100%. Filter tests performed in Kenya showed percent total coliform and *E. coli* removals of up to 99.995%. The Pelikan filters were the cheapest filters purchased, retailing for $2 in Nairobi. Results of viral removal studies indicated that the Pelikan filters were not effective at removing viruses from solution.

The results of this study support the use of Pelikan filters as an inexpensive and integral step in the household water treatment process. Sedimentation and/or coagulation are recommended pre-filtration if highly turbid water is to be filtered. This action will ensure a higher flow rate. Additionally, disinfection is recommended post-filtration to remove any residual bacteria.

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Thesis Supervisor: Martin Polz
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Acknowledgements

I would like to thank several people whose help made this thesis possible:

Susan Murcott – For offering continuous support and guidance during the course of this program; for introducing me to the world of water and sanitation in developing countries; for working alongside me to get this project finished.

Martin Polz – For offering advice and knowledge on the topic of my thesis; for graciously letting me use your lab to perform my research.

Eric Adams, Jerome Connor, Pete Shanahan, Patricia Glidden, Gayle Sherman, and Sara Goplin – For not only making this program possible, but enjoyable and efficient.

My fellow Majinites – Robert Baffrey, Suzanne Young, Pragnya Alekal, Brian Loux, Brian Robinson, Mike Pihulic – It was wonderful experiencing Kenya with you all. I couldn't pick a better group of people to work with on this project.

My fellow MEngers – For making this experience an entirely enjoyable one.

Joe Brown and Douglass Wait – for teaching me the coliphage methods; for donating advice and guidance whenever I called; for providing me with the materials needed to perform my research.

Issac Kilanzo – For hosting our team in Kenya and allowing us the chance to visit your country.

Jackson Gaichuhie Kingori – For providing Brian and I with constant support during our time in Kenya; for aiding us in any way possible; for providing any information I requested during the course of this project.

John Muasya Ndolo – For welcoming us into your lab; for supporting us in our research; for going out of your way to make sure we had what we needed to perform our studies.

Mercy Muthoni Wambugu and family – For welcoming Brian and I into your home and life; for providing us with motherly support during our time in Kenya.

Peter Mwandikwa, Angwenyi Michael Maobe, Paul Kimani Muagai, Judy Nyaguthii Githuto, Mathews Kimaru Mathenge, Lucy N. Wairire, Elizabeth Mungára, Asha Bakari, Philes Kamini Muki, and all other members of the Water Pollution Control lab – For aiding Brian and I in the completion of our experiments; for welcoming us into the lab with open arms; for teaching us about Kenyan life and culture.

Dana, Ben, Janelle, Sarah, and all those in Polz's lab – For showing me around and teaching me the basics about microbiology techniques.

My family and friends – For offering your love and support during the course of this program.

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1. Introduction

1.1 Global Impact of Water-Related Disease

Water is essential to the survival of humans and the planet. Yet over one-sixth of the world's population (1.1 billion people) currently lacks access to safe water (WHO/UNICEF, 2000). Each year, water-related diseases claim the lives of 3.4 million people, the majority of whom are children (Dufour et. al, 2003). In fact, the second leading cause of childhood mortality are diseases transmitted through water or feces (Lenton et. al, 2005). Water-related diseases can be grouped into four categories based on the route of transmission: waterborne diseases, water-washed diseases, water-based diseases, and insect vector-related diseases.

Table 1.1: Water-Related Diseases

Waterborne diseases: caused by the ingestion of water contaminated by human or animal faeces or urine containing pathogenic bacteria or viruses: include cholera, typhoid, amoebic and bacillary dysentery and other diarrheal diseases.
Water-washed diseases: caused by poor personal hygiene and skin or eye contact with contaminated water: include scabies, trachoma and flea, lice and tick-borne diseases.
Water-based diseases: caused by parasites found in intermediate organisms living in contaminated water: include dracunculiasis, schistosomiasis, and other helminths.
Water-related diseases: caused by insect vectors, especially mosquitoes, that breed in water: include dengue, filariasis, malaria, onchocerciasis, trypanosomiasis and yellow fever.

Taken from Gleick, 2002

In an attempt to curb these numbers, the United Nation (UN) Member States set a target under Goal 7 of the Millennium Development Goals (MDGs) in 2000 to "halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation (WHO/UNICEF, 2004)." This target builds upon the target of "full access to water supplies and sanitation for all," which was established by the UN General Assembly for the International Drinking Water Supply and Sanitation Decade of 1981-1990 (Mintz et. al, 2001).

Since the 1990s, significant improvements in safe water coverage and sanitation have been made. Approximately 816 million people have gained access to improved water sources, which include household connections, public standpipes, boreholes, protected dug wells, protected springs, and rainwater. Approximately 747 million people have gained access to improved sanitation facilities, such as pour-flush latrines, simple pit latrines, ventilated improved pit latrines, and connections to a public sewer or septic system (WHO/UNICEF, 2000, 2004). However, this increase in coverage has been just sufficient to keep pace with population growth. In fact, the number of people lacking access to safe water has remained relatively constant since 1990 (Mintz et. al, 2001).

If the world is to meet the set water and sanitation target by 2015, new approaches to obtaining safe water must be considered. Installation of centralized water treatment plants and pipe-distribution systems can not be relied upon as the sole method of supplying improved water. The ability of governments and private organizations to deliver piped water to dispersed populations in rural communities is poor, due to the large capital required to build and sustain such infrastructure. Instead of waiting for centralized water systems to be installed, people should look to point-of-use treatment as an immediate and sustainable alternative to obtaining safe water.

1.2 Point-of-Use Treatment

Decentralized point-of-use systems are viable options for improving water quality at the household level. These simple, inexpensive interventions have been shown to reduce diarrheal disease and deaths caused by microbially-contaminated drinking water (Clasen et. al, 2004, Mintz et. al, 2001, Sobsey, 2002). Studies of different technologies show reductions in household diarrheal diseases ranging from 6% to 90% (Sobsey, 2002). Chlorine disinfection appears to be the most effective household treatment method; the median reduction in endemic diarrheal disease resulting from chlorine disinfection studies (when compared with controls) is 46%. Filtration comes in second with a median reduction of 40%. Flocculation and combination flocculation/disinfection come in third with a median reduction of 38%. Solar radiation and heating studies reveal a median reduction of 35% (Clasen et. al, 2004).

Household water treatment methods can be classified as either chemical or physical. Chemical treatment options include chlorine disinfection; adsorption with carbon, clay, and plant materials; coagulation or adsorption with lime, alum, or plant extracts; and inactivation by germicidal metals such as copper and silver. Physical treatment options include sedimentation; boiling or heating; solar disinfection (UV irradiation and heating); and filtration (Sobsey, 2002). [See Tables 1.1 and 1.2]

Filtration in particular has emerged as a useful household treatment option. Ceramic water filters are recognized as "one of the most promising and accessible technologies for treating water at the household level (Clasen et. al, 2004)." These filters can be made from locally available materials and are relatively inexpensive. Ceramic water filters act by physically removing particles from solution. Many have the ability to remove disease-causing bacteria and parasites from contaminated water. For these reasons, ceramic water filtration appears to be a viable method of point-of-use water treatment.

Table 1.2: Chemical or Physical-Chemical Methods for Water Treatment at the Household Level

Method	Availability and Practicality	Technical Difficulty	Cost[a]	Microbial Efficacy[b]
Coagulation-Flocculation or Precipitation	Moderate	Moderate	Varies	Varies[c]
Adsorption (charcoal, carbon, clay, etc.)	High to moderate	Low to moderate	Varies	Varies with adsorbent[d]
Ion exchange	Low to Moderate	Moderate to high	Usually High	Low or moderate
Chlorination	High to Moderate	Low to Moderate	Moderate	High
Ozonation	Low	High	High	High
Chlorine Dioxide	Low	[illegible]	High	High
Iodination (elemental, salt or resin)	Low	Moderate to High	High	High
Acid or base treatment with citrus juice, hydroxide salts, etc.	High	Low	Varies	Varies
Silver or Copper	High	Low	Low	Low
Combined systems: chemical coagulation-flocculation, filtration, chemical disinfection	Low to Moderate	Moderate to High	High	High

[a] Categories for annual household cost estimates in US dollars are less than $10 for low, >$10-100 for moderate and >$100 for high.

[b] Categories for microbial efficacy are based on estimated order-of-magnitude or $\log_{10}$ reductions of waterborne microbes by the treatment technology. The categories are <1 $\log_{10}$ (<90%) is low, 1 to 2 $\log_{10}$ (90-99%) is moderate and >2 $\log_{10}$ (>99% is high).

[c] Varies with coagulant, dose, mixing and settling conditions and pH range.

[d] Microbial adsorption efficiency is low for charcoal and carbon and high for some clays.

[e] On-site generation of gas is difficult but chemical production by acidifying chlorate or chlorite is simple if measuring devices and instructions are provided.

Table 1.3: Physical Methods for Water Treatment at the Household Level

Method	Availability and Practicality	Technical Difficulty	Cost[a]	Microbial Efficacy[b]
Boiling or heating with fuels	Varies[c]	Low-Moderate	Varies[c]	High
Exposure to Sunlight	High	Low-Moderate	Low	Moderate
UV Irradiation (lamps)	Varies[d]	Low-moderate	Moderate-high[d]	High
Plain Sedimentation	High	Low	Low	Low
Filtration[e]	Varies[e]	Low-Moderate	Varies[e]	Varies[f]
Aeration	Moderate	Low	Low	Low[g]

[a] Categories for annual household cost estimates in US dollars are less than $10 for low, >$10-100 for moderate and >$100 for high.

[b] Categories for microbial efficacy are based on estimated order-of-magnitude or $\log_{10}$ reductions of waterborne microbes by the treatment technology. The categories are <1 $\log_{10}$ (<90%) is low, 1 to 2 $\log_{10}$ (90-99%) is moderate and >2 $\log_{10}$ (>99% is high).

[c] Depends on heating method as well as availability and cost of fuels, which range from low to high.

[d] Depends on availability of and type of lamps, housings, availability and cost of electricity, as well as operation and maintenance needs (pumps and system cleaning methods).

[e] Different filtration technologies are available. Some (e.g., membrane filtration) are recommended for emergency water treatment). Practicality, availability, cost and microbial efficacy depend on the filter medium and its availability: granular, ceramic, fabric, etc.

[f] Depends on pore size and other properties of the filter medium, which vary widely. Some are highly efficient (>>99% or >>2$\log_{10}$) for microbial removals.

[g] Aeration (oxygenation) may have synergistic effects with other water treatments, such as solar disinfection with sunlight or with other processes that may oxidize molecular oxygen.

Adapted from Sobsey, 2002

Upon recognizing the positive effects of ceramic filters and other such household water treatment methods, WHO established the International Network for the Promotion of Safe Household Water Treatment and Storage (The Network), in collaboration with the UN, bilateral agencies, private sector companies, NGO's, and research institutions such as MIT (WHO, 2005). The goal of this Network is to promote household water treatment and safe storage technologies (HWTS) in an attempt to "accelerate health gains to those without reliable access to safe drinking water (WHO, 2005)." MIT has been involved in this network since its inception. MIT students recently traveled to Kenya to perform research on household water treatment systems.

1.3 MIT Kenya Project

In January of 2005, a group of seven MIT Master of Engineering students, along with four MIT business students and one Harvard School of Public Health student, traveled to Kenya in an effort to observe, study, and improve upon current household water treatment and sanitation practices. Students worked with partner organizations such as the Kenyan Ministry of Water, the Kenya Water for Health Organization (KWAHO), the Center for Disease Control, CARE-Kenya, the Society for Women and Aids in Kenya (SWAK), and Population Services International (PSI).

Pragnya Alekal and the business team, Ellen Sluder, Jody Gibney, Mark Chasse, and Rachel Greenblat worked with SWAK, CARE and PSI in Kisumu. Alekal performed household surveys and tests with regard to chlorine disinfection (Waterguard) and coagulation/flocculation products (PuR) (Alekal, 2005). The business team evaluated the business and marketing operations of organizations distributing Waterguard and PuR.

Suzanne Young and Mike Pihulic visited various pottery organizations in and around Homa Bay in an attempt to document the pot-making process and develop a standardized safe storage container that could be used with disinfection products (Young, Pihulic, 2005). Young and Pihulic worked with the CDC and CARE-Kenya.

Brian Loux and Amber Franz were stationed at the Ministry of Water's Pollution Control Division in Nairobi. Loux developed and tested modified solar disinfection systems (Loux, 2005). Franz performed testing of several locally available brands of ceramic water filters. Franz examined flow rate, turbidity removal, and bacterial removal for each of the filters while in Kenya.

Brian Robinson examined ecological sanitation (EcoSan) toilets as an improved sanitation facility option in the district of Kombewa (Robinson, 2005). Robinson worked in conjunction with KWAHO, performing household surveys and urine testing at each EcoSan site he visited.

Robert Baffrey and Harvard School of Public Health student Jill Baumgartner interviewed multiple water and health-related organizations in an attempt to gather information on various implementation techniques and household treatment methods (Baffrey, 2005). Their work supported the activities of the Implementation Working Group of the WHO International Network. Hosted by the Ministry of Water, Baffrey and Baumgartner traveled to several

locations in Kenya, including Nairobi, Mombasa, Maseno, Machakos, Nakuru, Eldoret, and Kisumu (See Figure 1.1).

1.4 Background on Kenya

Located in sub-Saharan Africa, the Republic of Kenya is bordered by Ethiopia and Sudan to the north, Uganda and Lake Victoria to the west, Tanzania to the southwest, the Indian Ocean to the southeast, and Somalia to the East. The country has a land area of 566,970 square km (218,907 square miles). Kenya has two rainy seasons, which occur from April to June and from October to December. Despite this, and the fact that Kenya is located in the tropical region on the equator, annual rainfall in Kenya is very low and erratic from year to year. Both droughts and floods pose serious problems (World Atlas, 2005).

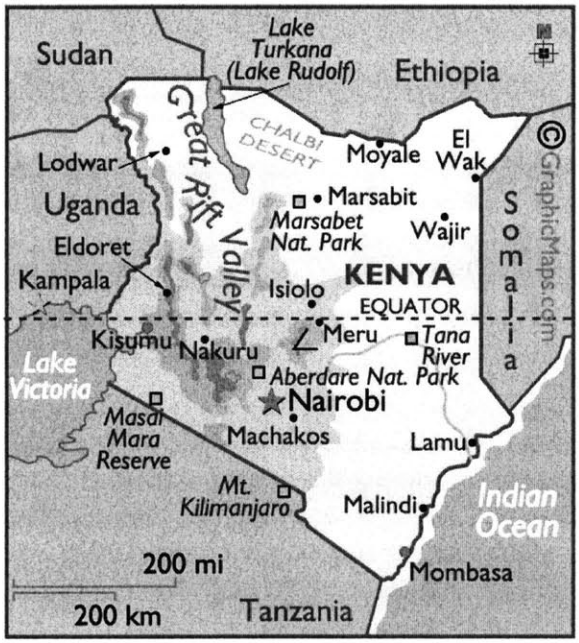


Figure 1.1: Map of Kenya

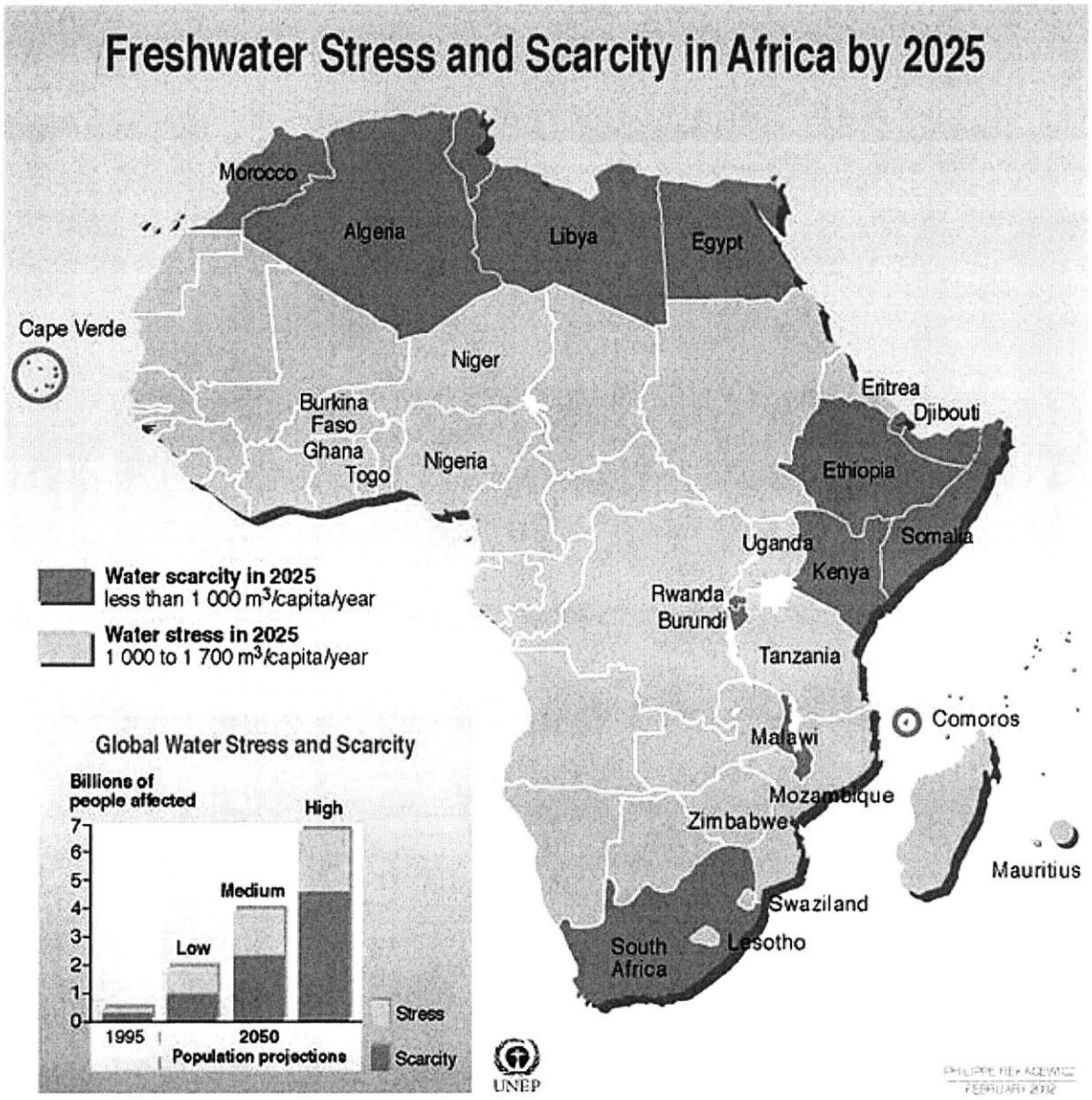
Taken from WorldAtlas.com

Kenya has a population of around 32 million, and a growth rate of 1.14%. Coupled with erratic rainfall and droughts, the quickly growing population has led to a steady decline in the availability of renewable freshwater. According to the United Nations, a country is considered to be "water stressed" if its renewable freshwater supply ranges from 1,000 to 1,700 cubic meters per person per year (UNEP, 2002). Countries possessing a supply below 1,000 cubic meters per person per year are considered to be "water scarce." In 1990, twenty nations were added to the "water scarce" list (Engelman and LeRoy, 1993). Kenya was one of them; its annual per capita renewable freshwater supply was 647 cubic meters as of 1999 (Kiongo, 2005).

Table 1.4: Countries experiencing water scarcity in 1955, 1990 and 2025 (projected), based on availability of less than 1,000 cubic meters of renewable water per person per year

Water-scare countries in 1955	Countries added to scarcity category by 1990	Countries added to scarcity category by 2025 under all UN population growth projections	Countries added to scarcity category by 2025 only if they follow UN medium or high projections*
Malta	Qatar	Libya	Cyprus
Djibouti	Saudi Arabia	Oman	Zimbabwe
Barbados	United Arab Emirates	Morocco	Tanzania
Singapore	Yemen	Egypt	Peru
Bahrain	Israel	Comoros	
Kuwait	Tunisia	South Africa	
Jordan	Cape Verde	Syria	
	Kenya	Iran	
	Burundi	Ethiopia	
	Algeria	Haiti	
	Rwanda		
	Malawi		
	Somalia		

Adapted from Engelman and LeRoy, 1993



Source: United Nations Economic Commission for Africa (UNECA), Addis Ababa; Global Environment Outlook 2000 (GEO), UNEP, Earthscan, London, 1999; Population Action International.

Figure 1.2: Freshwater Stress and Scarcity in Africa by 2025

The water scarcity situation makes it difficult to obtain safe water. In Kenya, 62% of the people use improved drinking water sources. Approximately 39% of the total population occupies urban areas; 89% of the urban population has access to improved water sources and 56% has access to adequate sanitation[1]. Comparatively, of the remaining 61% of the population that occupies rural areas, only 46% has access to improved water supplies and a mere 43% has access to adequate sanitation (UNICEF, 2002).

[1] Those considered to possess access to adequate sanitation are those using the improved sanitation facilities defined in Section 1.1.

In Nairobi specifically, where the author performed her research, 55% of the city's population is squeezed into informal settlements (i.e. slums) that occupy only 6% of the city's land area. Only 12% of these residents have access to piped water and a shocking 6% have access to adequate sanitation. Kibera is the largest slum in Africa, where an estimated population of 500,000 to 750,000 inhabits an area of 2.25 square kilometers (0.87 sq mi) (Salmon, 2002; UN-Habitat, 2003). Rivers of sewage flow through towns where children play in bare feet. The lack of safe water and sanitation resulting from these conditions reveals the need for serious improvements. Decentralized point-of-use systems offer an immediate solution to the problem of obtaining safe drinking water for home use.

1.5 Research Goals

The goal of this study is to assess the performance of ceramic water filters that are locally available in Kenya. Five brands of filters will be evaluated based on cost, flow rate, turbidity removal, and microbial removal. Filters that perform the best at removing bacteria (total coliforms and *E. coli*) will be further tested for viral removal. Results from this study will be translated into recommendations regarding the best-performing ceramic water filter(s).

This research falls under the bigger aim of reducing the spread of waterborne disease. By encouraging and identifying methods that are capable of removing disease-causing organisms from drinking water, the quality of life of the world's most vulnerable citizens will improve. Illness and death caused by consumption of contaminated water will decline and people will have the opportunity to live happier, healthier, more productive lives.

2. Waterborne Disease

2.1 Waterborne Pathogens

Microbial contamination of drinking water is a major factor in the spread of disease. Pathogens are the agents responsible for infectious disease, and can infect humans via ingestion, inhalation, or contact with skin, wounds, eyes, or mucous membranes (WHO, 2004). Most pathogens are introduced into drinking water sources by human or animal waste, and can not proliferate in water (WHO, 2004). Pathogens transmitted through this route are dubbed "enteric" because they initially occupy a niche in the intestines, or enteron, of their host. Upon leaving their host, the viability and infectivity of pathogens tend to decrease exponentially (WHO, 2004). Pathogens possessing a high resistance to decay are the most problematic when it comes to waterborne disease. Some of the pathogens most relevant to drinking water include certain bacteria, viruses, protozoa, and helminthes; these pathogens are described in detail below.

2.1.1 Bacteria

Bacteria are unicellular microorganisms that lack a nucleus (prokaryotes). All bacteria possess certain structures in common. The cell wall is composed of murein and teichoic acids, and is resistant to hydrophobic substances and desiccation. The cell membrane is composed of a phospholipid bilayer that is semipermeable and resistant to hydrophilic molecules. The cell membrane and cell wall encompass the internal constituents of a bacterium, protecting it from the outside world. Within a bacterium, ribosomes and DNA are suspended in a dense gel matrix called the cytoplasm. Bacteria come in a variety of shapes and sizes; they can be rod-shaped (bacillus), spherical (coccus), spiral-shaped (spirillum), etc. A typical bacillus has a length of 1-5 μm and a width of 1 μm, although bacteria can range in size from 0.1-600 μm depending on their species and nutritional state (Madigan et. al, 2003).

Depending on their specific properties, certain bacteria can be more pathogenic than others. For example, members of the family enterobacteriaceae (phylum Proteobacteria) are notorious for their pathogenicity. Microorganisms within this family are gram-negative enteric bacilli that ferment glucose and reduce nitrate (Enterobacteriaceae Summary, 2000). Species within this family that are significant waterborne pathogens include *Escherichia coli, Salmonella typhi, Shigella spp.*, and *Yersinia enterocolitica.*

Escherichia coli are normal, harmless inhabitants of the intestines of humans and animals. However, exposure of certain *E. coli* strains to other parts of the body can result in serious illness, such as urinary tract infections and meningitis (WHO, 2004). Certain pathogenic strains of *E. coli* can cause mild to highly bloody diarrhea. *E. coli* is spread from contact with infected individuals or food, and consumption of contaminated water.

Salmonella typhi are motile bacilli that are responsible for a variety of symptoms upon infection, including diarrhea, nausea, vomiting, and fever. *Salmonella typhi* are responsible for Typhoid fever, a severe and possibly fatal illness. *Salmonella typhi* infections are associated with consumption of contaminated food and water (WHO, 2004).

Shigella spp. grow in aerobic or anaerobic conditions, and can cause severe intestinal disease, such as bacillary dysentery (WHO, 2004). Each year, *Shigella spp.* infect 2 million people and kills 600,000; a majority of those infected are children under 10 years of age. Symptoms of the disease include abdominal cramps, bloody diarrhea, and fever. *Shigella spp.* inhabit the epithelial cells of their host's intestines, and are spread through contact with infected individuals or consumption of contaminated food and water; flies can transmit the disease after coming into contact with fecally contaminated waste.

Yersinia enterocolitica "penetrate cells of the intestinal mucosa," resulting in gastroenteritis, diarrhea, abdominal pain, enlarged lymph nodes, and fever (WHO, 2004). Although certain non-pathogenic strains are commonly found in the environment, pathogenic *Yersinia enterocolitica* are often present in sewage and contaminated water. Transmission of these bacteria occurs mainly through consumption of contaminated foods, although consumption of contaminated water or contact with infected individuals can also result in infection.

2.1.2 Viruses

Viruses are static, non-cellular organisms that range in size from 0.02 to 0.3 μm. Viruses are composed of an outer shell, or capsid, which consists of proteins that are arranged in a "precise and highly repetitive pattern (Madigan et. al, 2003)." These proteins encompass a virus's genetic information, which can be in the form of double or single-stranded DNA or RNA. Viruses are considered to be non-cellular because they need a host cell in order to reproduce. All cells are susceptible to viral infection. The infective cycle starts when a viruses attaches to specific surface structures of its host. The virus then injects its genetic information into the cell. The viral nucleic acid redirects the cell's metabolism to make more viral DNA/RNA and proteins. Next, the newly synthesized viral genetic material is packaged into a protective shell. The host cell is eventually lysed, expunging fresh virus particles (Madigan et. al, 2003).

Viruses responsible for disease may either destroy their host cell after replication or insert their genome into the host genome. The pathogenic viruses found in contaminated water tend to originate from the gastrointestinal tracts of humans (excreted in feces). These viruses are "critical target organisms to control because they are responsible for approximately 80% of waterborne disease outbreaks for which infectious agents were identified (Cadmus, 2000)." Some of the more potent enteric viruses include adenoviruses, enteroviruses, hepatitis A and E, and rotaviruses (WHO, 2004).

Adenoviruses consist of a 0.08 μm icosahedral capsid that encompasses double-stranded DNA. Adenoviruses can infect amphibians, birds, and mammals. Human adenoviruses (HAds) are classified into six groups, and can infect the eyes, respiratory tract, urinary tract, and gastrointestinal tract, resulting in keratoconjunctivitis, pharyngoconjunctival fever, pneumonia, acute respiratory diseases, cervicitis, urethritis, haemorrhagic cystitis, and gastroenteritis (WHO, 2004). HAds can be transmitted through contact with a contaminated individual, or through consumption or contact with contaminated food or water. HAds have been found in raw and treated water sources; they are extremely resistant to certain disinfection and water treatment processes.

Enteroviruses consist of a 0.02-0.03 μm icosahedral capsid that encompasses a single strand of RNA. Enteroviruses can infect both humans and animals. Among humans, they "have been estimated to cause about 30 million infections in the USA each year (WHO, 2004)." Some of the illnesses caused by enteroviruses include meningoencephalitis, poliomyelitis, hand-foot-and-mouth disease, and chronic fatigue syndrome. Enteroviruses can be spread through contact with an infected individual, inhalation of airborne particles, and possibly consumption of fecally contaminated water (WHO, 2004).

Like enteroviruses, Hepatits A viruses (HAVs) consist of a 0.02-0.03 μm icosahedral capsid that encompasses a single strand of RNA. HAVs infect the epithelial cells of the gastrointestinal tract, where they enter the bloodstream and damage the liver (WHO, 2004). Symptoms include fever, nausea, anorexia, jaundice, and dark urine. HAVs can be spread through contact with an infected individual, drug use, or consumption of contaminated food and water. Among viruses, HAVs have the most evidence for waterborne transmission.

Hepatitis E viruses consist of a 0.027-0.034 μm icosahedral capsid that encompasses a single strand of RNA (WHO, 2004). Symptoms of Hepatitis E infection are similar to those caused by HAV. However, there is a longer incubation period for Hepatits E viruses. The main route of transmission is contact with/consumption of contaminated drinking water, although spread of the virus through contact with an infected individual may also occur.

Rotaviruses consist of a double-layered shell covering a 0.05-0.065 μm icosahedral capsid that encompasses double-stranded RNA. Rotaviruses can infect both animals and humans. Human rotaviruses (HRVs) are the "leading cause of childhood diarrhea worldwide, causing an estimated 600,000 deaths each year (Jain et. al, 2001). HRVs infect the villi of the small intestine, resulting in watery diarrhea, dehydration, abdominal pain, vomiting, and fever (WHO, 2004). Contact with an infected individual and inhalation of airborne particles are the major routes of transmission of HRVs, although consumption of contaminated food and water may also occur.

2.1.3 Protozoa

Protozoa are unicellular microorganisms that have a nucleus (eukaryotes). Protozoa are larger than bacteria and viruses, but are still microscopic (range in size from a few μm to several mm). Protozoa lack a cell wall, but possess a cell membrane that surrounds the cytoplasm. Within the cytoplasm, various organelles reside, such as the nucleus, mitochondria, and vacuoles. Protozoa are characterized by their motility. Protozoa move by either amoeboid action, cilia, or flagella (Madigan et. al, 2003). Once they reach a food source, protozoa generally feed by phagocytosis; they surround the food particle with their cell membrane and engulf it, bringing it into the cell to be digested by enzymes.

Protozoa are responsible for infections and disease in humans and animals. Transmission of these pathogens by water is common. However, treatment methods are often ineffective when protozoa are in the form of cysts. Protozoa present in this form are protected from extreme temperatures, pHs, and dehydration by a resistant wall that surrounds the microorganism

(Protozoan Parasites, 2004). Some of the more infectious waterborne protozoa species include *Acanthamoeba* spp., *Cryptosporidium parvum*, *Giardia intestinalis*, and *Toxoplasma gondii*.

Acanthamoeba spp. are "free-living amoebae common in aquatic environments" and soil (WHO, 2004). *Acanthamoeba* spp. range in size from 10-50 μm and are capable of developing into dormant cysts. Infection by *Acanthamoeba* spp. can result in such illnesses as granulomatous amoebic encephalitis (GAE) and acanthamoebic keratitis. GAE has symptoms of headache, drowsiness, stiffness, nausea, personality changes, vomiting, and seizures, among others. Acathamoebic keratitis is an infection of the cornea, and can result in impaired vision, blindness, and loss of the eye. *Acanthamoeba* spp. can be transmitted through tap water and blood (WHO, 2004).

Cryptosporidium parvum is an intracellular parasite whose 4-6 μm oocysts are expelled in the host's feces. Infectious oocysts have their sources in humans and animals, and can survive for months in fresh water *Cryptosporidium parvum* is the main species of Cryptosporidium responsible for human infections; symptoms of infection include fever, nausea, vomiting, and diarrhea. *Cryptosporidium parvum* can be spread through contact with an infected individual and consumption of contaminated food and water. *Cryptosporidium parvum* was responsible for the "largest waterborne outbreak of disease on record, when more than 400,000 people were infected by the drinking-water supply of Milwaukee, USA" in 1993 (WHO, 2004).

Giardia intestinalis is a flagellated parasite of the intestinal tracts of humans and animals. Ovoid 8-12 μm cysts are shed in the host's feces. Upon infection, an individual will experience nausea, vomiting, bloating, and diarrhea. If acute cases become chronic, an individual will suffer from diarrhea, fatty stools, and weight loss due to malabsorption of nutrients. *Giardia intestinalis* is spread through contact with infected individuals, and fecally contaminated water. *Giardia intestinalis* is "the most common cause of protozoan diarrheal illness worldwide (Cotruvo et. al, 2004)."

Toxoplasma gondii is an intracellular parasite for which cats are the host. Resistant 10x12 μm oocyts are excreted in the feces (Cotruvo et. al, 2004). Upon infection by *Toxoplasma gondii*, most individuals are asymptomatic. However, some people show signs of lymphadenopathy, pneumonia, neurological disorders, cerebral calcifications, convulsions, etc. *Toxoplasma gondii* is spread through contact with infected individuals, or contaminated soil or water (WHO, 2004).

2.1.4 Helminths

Parasitic helminths are multi-cellular worms and flukes that occupy the intestinal tracts of vertebrates (Webster, 2004). Helminths possess complex reproductive systems and can be microscopic to several feet in length. The life cycles of helminths can be categorized as either direct or indirect. In the direct life cycle, helminths have only one definitive host, with a "free-living phase during which they develop to the infective stage (Cotruvo et. al, 2004)." In the indirect life cycle, helminths have a definitive host in addition to one or more intermediate hosts, and a free-living stage between hosts.

People and animals act as hosts for these organisms. Infection usually occurs through the mouth, through contact with contaminated soil, water, food, insects, or infected individuals can also result in the spread of helminths (Cotruvo et. al, 200). Species for which water plays a major role in transmission include *Dracunculus medinensis* and *Fasciola* spp. (WHO, 2004).

Dracunculus medinensis is also known as the guinea worm, and resides in the connective, cutaneous, and subcutaneous tissue of infected individuals. Adult females range in size from 750 to 1200 mm, while adult males reach a length of only 25 mm (Cotruvo et. al, 2003; WHO, 2004). Female guinea worms discharge larvae by poking their anterior ends through the skin, forming blisters. When the blister is submerged in water, the larvae are released. Here they are ingested by *Cyclops*, a small crustacean. After molting twice, the worms can infect people and animals that might ingest *Cyclops* species through drinking contaminated water. Symptoms of infection include erythema, vomiting, giddiness, and possibly an inflammatory reaction originating from infection of the worm track.

Fasciola spp. (liver flukes) that are spread through water include *Fasciola hepatica* and *Fasciola gigantica*. *Fasciola hepatica* has an average size of 20-30 mm. Hosts of the flukes include snails and vertebrates. When released from the snails into the water, the organisms attach to aquatic plants. Ingestion of these plants or water results in infection. Once inside the vertebrate host, the flukes migrate to the liver and bile ducts (WHO, 2004). Here they release their eggs, which are excreted by the host in feces. Symptoms of infection include abdominal pain, fever, vomiting, anemia, and eventually liver enlargement, chest pains, and weight loss.

2.2 Microbial Indicators of Waterborne Pathogens

Multiple methods have evolved for the detection and enumeration of pathogens. However, these tests are often costly, complex, and time consuming (WHO, 2004). Additionally, it is impractical to test for all of the possible pathogens present in a water source. For these reasons, water is often tested for indicator microorganisms. Indicator microorganisms are organisms "whose presence points to the possible occurrence" of pathogens (Dufour et. al, 2003). Indicator microorganisms are used to reveal the effectiveness of water treatment methods. Knowledge of waterborne pathogens and microbial indicators is paramount if people are to avoid and/or properly treat contaminated water supplies, and ultimately reduce the spread of illness and disease.

The concept of the indicator evolved from the fact that certain non-pathogenic microorganisms are present in the feces of all warm-blooded animals (Gerba, 2000). This reality was first studied by Escherich in 1885, who noticed the presence of certain microbes in the feces of infants. Escherich named these microorganisms *Bacterium coli*. In 1892, Schardinger proposed that "since *Bacterium coli* was a characteristic component of the fecal flora, its presence in water could be taken as 'an indication of the presence of fecal pollution and therefore of the potential presence of enteric pathogens' (Dufour et. al, 2003)." Soon thereafter, other gram-negative, lactose-fermenting bacteria were isolated and grouped under the name "coliforms." Since then, other enteric microorganisms have emerged as possible indicators of fecal contamination. In response to this, criteria have been established for ideal microbial indicators. According to the World Health Organization (WHO) Guidelines for Drinking-Water Quality, an indicator should:

- Be universally present in the feces of humans and animals in large numbers;
- Not multiply in natural waters;
- Persist in water in a similar manner to fecal pathogens;
- Be present in water in higher numbers than fecal pathogens;
- Respond to treatment processes in a similar fashion to fecal pathogens; and be readily detectable by simple, inexpensive methods (WHO, 2004)

Several microorganisms have surfaced as suitable indicators, but to date no single microorganism fits all the criteria. Some of the most frequently used bacterial indicators include total coliforms, thermotolerant (fecal) coliforms, *Escherichia coli*, and fecal streptococci and intestinal enterococci. Certain bacteriophages, such as F-RNA (male-specific) coliphages, somatic coliphages, and *Bacteroids fragilis* phages, are often used as viral indicators. *Clostridium perfringens* has been proposed as both a viral and protozoal indicator.

2.2.1 Bacterial Indicators

Total coliforms are defined as all aerobic and facultatively anaerobic "gram-negative, non-spore-forming, rod-shaped bacteria capable of growth in the presence of bile salts or other surface-active agents with similar growth-inhibiting properties, oxidase-negative, fermenting lactose at 35-37°C with the production of acid, gas, and aldehyde within 24-48 hours (Dufour et. al, 2003)." Total coliforms have been used in the past as indicators of water contamination because they are easily detectable. However, because coliforms have the ability to survive and multiply in natural waters, their effectiveness as indicators of fecal contamination is compromised. Additionally, studies have shown that there is no direct correlation between the presence of pathogens and the presence of total coliforms (Borchardt et. al, 2003). Instead, total coliforms can be better used to assess treatment methods; their presence in filtered or disinfected water reveals inadequate treatment (WHO, 2004).

Thermotolerant (fecal) coliforms are a subset of the total coliform group that is able to ferment lactose at temperatures of 44-45°C. Thermotolerant coliforms include the genera *Escherichia*, *Klebsiella*, *Enterobacter*, and *Citrobacter*. Thermotolerant coliforms may not be solely of fecal origin. These bacteria are capable of multiplying in the soil in tropical climates (Byappanahalli, 1998). This means that the presence of thermotolerant coliforms does not necessarily indicate fecal contamination. However, under most circumstances, thermotolerant coliform concentrations correlate with *E. coli* concentrations. Thermotolerant coliforms are somewhat sensitive to disinfection processes; these coliforms are inactivated by light at a greater rate than other indicator microorganisms (Davies-Colley et. al, 1994; Sinton et. al, 2002).

Escherichia coli are thermotolerant coliforms that belong to the total coliform group. *E. coli* are differentiated from thermotolerant coliforms by their ability to "produce indole from tryptophan or by the production of the enzyme β-glucuronidase (WHO, 2004)." *E. coli* has been found to be present in fresh feces in concentrations as high as 10^9 per gram. The presence of *E. coli* is also detectable by simple, inexpensive methods (Dufour et. al, 2003). Although studies have shown that *E. coli* is capable of growing and multiplying in soil in tropical and subtropical environments, environmental conditions outside of these climates are unlikely to support *E. coli* growth outside of the intestine (Byappanahalli, 1998; Desmarais, 2002). For these reasons, *E. coli* has come to be

the preferred indicator of choice for fecal contamination. However, like other coliforms, *E. coli* is more sensitive to treatment and disinfection than other pathogens; its absence in treated waters does not necessarily reveal the absence of all pathogens.

Fecal streptococci are anaerobic, gram-positive bacteria belonging to the genus *Streptococcus* that possess the Lancefield group D antigen (Gerba, 2000). True fecal streptococci include *S. bovis* and *S. equines*. These two species are found mainly in animal intestines. A subgroup of fecal streptococci is the intestinal enterococci. These bacteria belong to the genus *Enterococcus* and are "differentiated from other streptococci by their ability to grow in 6.5% sodium chloride, pH 9.6, and 45°C (Gerba, 2000)." Species include *Ent. avium, Ent. faecium, Ent. durans, Ent. facculis,* and *Ent. gallinarium.* These enterococci are used by the Environmental Protection Agency to indicate contamination of recreational waters. Because intestinal enterococci have mainly fecal origins, they have succeeded fecal streptococci as indicators of fecal pollution. Yet, like *E. coli*, enterococci are capable of growth in the soils in subtropical environments (Desmarais, 2002). Enterococci are present in large numbers, though they are not as numerous as *E. coli.* Although enterococci are relatively susceptible to inactivation by light when compared to other indicator microorganisms, both fecal streptococci and intestinal enterococci are more resistant to stress and chlorination than the coliform bacteria (Davies-Colley et. al, 1994; Sinton et. al, 2002; Dufour et. al, 2003). This advantage supports the use of fecal streptococci and intestinal enterococci as indicators of water treatment methods. However, because they are anaerobic, special precautions must be made when testing for fecal streptococci and intestinal enterococci. This constraint makes fecal streptococci and intestinal enterococci somewhat more difficult to test for than coliforms.

2.2.2 Viral Indicators

Bacteriophages are viruses that use bacteria as hosts for replication (WHO, 2004). One type of bacteriophage, the F-RNA coliphage, consists of "an icosahedral capsid with a diameter of about 0.025 μm and a single stranded (ss)-RNA genome (Grabow Update, 2001). F-RNA coliphages infect *E. coli* and other gram-negative bacteria possessing the F-plasmid, which codes for the fertility fimbriae or sex pili. F-RNA coliphages adsorb solely to the sex-pili, which are synthesized at temperatures above 30°C. This means that it is unlikely that F-RNA coliphages will infect bacteria and replicate in environments other than the gut of warm-blooded animals (Grabow Update, 2001). F-RNA coliphages also possess many attributes of human enteric viruses, including morphology, physical structure, composition, and size and site of replication. Additionally, F-RNA coliphages are resistant to various chemicals, heat, UV light and sunlight, chlorination, and water treatment processes (Grabow Update, 2001; Sinton et. al, 2002). Unfortunately, F-RNA coliphages are still lacking in certain criteria associated with ideal indicator organisms. For example, as of yet there is no direct correlation between the number of coliphages and the number of enteric viruses present in polluted water (e.g. Borchardt et. al, 2003). Thus coliphages can not be used to indicate the amount of viruses present in the water. Additionally, small concentrations of enteric viruses have been detected in drinking water supplies in which there were no F-RNA coliphages present (Grabow Update, 2001). Also, compared to *E. coli*, the number of coliphages present in contaminated water is much lower. This may be due to the fact that only about 3-10% of individuals carry F-RNA coliphages (Leclerc et. al, 2000). For these reasons, F-RNA coliphages should not be used as the sole indicators of water quality. Rather, their resilience lends them to use as indicators of the effectiveness of water treatment methods.

Somatic coliphages belong to a variety of families, including Myoviridae, Siphoviridae, Podoviridae, and Microbiridae. These coliphages infect *E. coli* and related members of the family Enterobacteriacea via cell wall receptors (Grabow Update, 2001). Somatic coliphages replicate mainly in the intestinal tract, though they have been shown to replicate in water as well. Somatic coliphages are present in larger numbers than F-RNA coliphages (Sundram et. al, 2002). Like F-RNA coliphages, somatic coliphages are more resilient than coliforms. However, as of yet there is no established correlation between the number of somatic coliphages and the number of viral pathogens present in contaminated water. For these reasons, somatic coliphages would be better suited as indicators of the effectiveness of water treatment methods.

Bacteroids fragilis phages infect *Bacteroids fragilis* bacteria, which are present in the intestine in higher numbers than coliforms (10^9-10^{10}/g feces vs. 10^6-10^8/g feces for coliforms). *Bacteroids fragilis* bacteria are strict anaerobes, and are inactivated by oxygen, limiting their use as indicators (Grabow Update, 2001). However, *Bacteroids fragilis* phages are resilient organisms that may have some use as indicators of viral contamination. *Bacteroids fragilis* phages have a "decay rate similar to that of human enteric viruses" and are found in 5-25% of the human population (Dufour et. al, 2003). *Bacteroids fragilis* phages can be divided into two groups. Phages of the first group belong to the family Siphoviridae, and possess flexible tails, ds-DNA, and 60 nm capsids (WHO, 2004). These phages use *Bacteroids fragilis* strain HSP40 as hosts, and are found only in human feces. Concentrations of these phages in sewage are quite low. *Bacteroids fragilis* phages of the second group use *Bacteroids fragilis* strain RYC2056 as hosts. These phages are found in both humans and animals and are present in sewage in higher concentrations than phages of the previous group. It should be noted that tests for *Bacteroids fragilis* phages are somewhat more complicated than assays for somatic and F-RNA coliphages due to the anaerobic conditions required for host bacteria.

2.2.3 Protzoal and Viral Indicator

Clostridium perfringens has been purported to serve as both a protozoal and viral indicator. *Clostridium perfringens* are "gram-positive, anaerobic, sulfite-reducing bacilli" that produce spores that are resistant to UV irradiation, extreme temperatures and pHs, and disinfection processes (WHO, 2004). *C. perfringens* has fecal origins, and is present in about 13-35% of humans and animals. *C. perfringens* does not replicate in the environment (Desmarais, 2002). Additionally, concentrations of *C. perfringens* have been shown to correlate with concentrations of enteric viruses and protozoal cysts (Payment, 1993). The resistant spores have been proposed as indicators of the presence of viral or protozoal pathogens. However, *C. perfringens* may be limited as a fecal contamination indicator because it may remain long after pathogens have died off. Rather, *C. perfringens* may be better utilized as an indicator of the effectiveness of water treatment processes, or as an indicator of past pollution. Techniques used to detect and enumerate *C. perfringens* are somewhat more complicated and expensive than tests for coliforms or enterococci due to their anaerobic nature.

2.2.4 Indicators Used in Study

According to the World Health Organization (WHO), *E. coli* is "the most suitable index of fecal contamination (WHO, 2004)." This is due to the fact that *E. coli* is of fecal origin; is present in high concentrations; does not replicate in waters in temperate climates; and is detectable by simple, cheap methods. F-RNA coliphages are recommended as complementary indicators because they are of fecal origin; they are unlikely to replicate in water; they possess many of the attributes of human enteric viruses, including morphology, physical structure, composition, and size and site of replication; they are resistant to various water treatment processes; and they are detectable by relatively simple methods (compared to *Bacteroids fragilis* phages and anaerobic indicators). Total coliforms, though unsuitable as indicators of fecal contamination, may be effective indicators of water treatment because they are easily detectable using simple experimental methods.

This research uses total coliforms, *E. coli*, and F-RNA coliphages to determine the effectiveness of ceramic candle filters at removing microbial contamination.

2.2.4.1 Tests for Total Coliforms and E. coli

Both total coliforms and *E. coli* can be detected by several procedures, including the membrane filtration (MF) test, most probably number (MPN) test, and Presence/Absence (P/A) test. In the MF test, a water sample is filtered and the filtrate incubated with growth media at 35-37°C for 24 hours. Colonies are then counted. In the MPN test, growth media and different dilutions of the water sample are placed in separate tests tubes. After incubation at 35-37°C for 48 hours, the tubes are examined for bacteria. Estimations of total coliforms/*E. coli* numbers are made based on positive results of different dilutions. Tubes possessing total coliforms/*E. coli* are then used to inoculate agar. Growth of colonies on the agar reveals the presence of total coliforms/*E. coli* in the sample. In the P/A test, broth and water sample are added to a test tube, along with certain salts and enzymes. If total coliforms/*E. coli* are present in the water sample, the liquid in the test tube will change color.

For this research, the membrane filtration (MF) test is the assay of choice for the detection and enumeration of total coliforms and *E. coli.* This method was selected over alternative methods for several reasons. First of all, the MF method can detect the presence of total coliforms and *E. coli* simultaneously (USEPA, 2003). The simple assay also uses easily transportable equipment, allowing for tests to be carried out in the field. When compared to the MPN test, the MF method reveals results in 24 hours versus 48-96 hours (Water Microbiology, 1992). Results obtained using the MF method also have greater precision than results obtained via the MPN test. Finally, the MF method allows for the analysis of large volumes of water (Water Microbiology, 1992).

In membrane filtration, a sample of water passes through a filter possessing 0.45 μm pores. Because bacteria such as *E. coli* are slightly larger than the pore size (1x3 μm), bacteria present in the water will collect on the surface of the filter (Madigan, 2002). Once filtration is complete, a nutritive broth is supplied to the filter in a petri dish. In this research, m-coliBlue24 was the broth used. This broth is a nutritive, lactose-based medium that contains inhibitors that prevent the growth of non-coliforms (USEPA, 2003). After incubation at 35°C ± 0.5°C for 24 hours, individual bacterial cells will have replicated, producing colonies that consist of millions of clones

of the original bacterium. These colonies are visible to the human eye and are defined as colony forming units (CFUs). A selective dye present in the broth, 2,3,5-Triphenoltetrazolium Chloride (TTC), highlights total coliform colonies in red. Among these coliforms, any colonies originating from an *E. coli* bacterium are highlighted in blue via the action of the *E. coli* β -glucuronidase enzyme on 5-Bromo-4-Chloro-3-Indolyl-β-glucuronide (BCIG) (USEPA, 2003). Thus total coliform and *E. coli* colonies can be differentiated from one another through this method.

In this thesis, the number of colonies present pre and post-filtration were compared to determine total coliform and *E. coli* removal efficiencies of the studied ceramic candle filters.

2.2.4.2 Tests for F-RNA Coliphages

The methods used for the detection and enumeration of F-RNA coliphages are somewhat more complicated than those used for total coliforms and *E. coli*. However, testing for F-RNA coliphages is still simpler than testing water for a variety of pathogens. Tests for F-RNA coliphages include the P/A test and plaque assays. In plaque assays, a water sample is mixed with host bacteria and agar at temperatures above 30°C and incubated for 24 hours. F-RNA coliphages that infect the host cells will be present on the plates as plaques (lysis zones), which can be counted and used to estimate the number of F-RNA coliphages present in the original sample (Method 1602, 2001).

The Double Agar Layer (DAL) procedure, outlined in EPA Method 1602: Male –specific (F^+) and Somatic Coliphage in Water by Single Agar Layer (SAL) Procedure, was followed for the purpose of quantifying F-RNA coliphages present in contaminated water sources (Method 1602, 2001). Douglass Wait, lab manager of Professor Mark Sobsey's microbiology lab in the Department of Environmental Science and Engineering at UNC, was kind enough to train the author in this method over Christmas break. This method was selected for its clarity and ability to quantify the amount of coliphages present in a sample. In this procedure, a water sample is added to molten 0.8% tryptic soy agar (TSA), along with *E. coli* F_{amp} or *E. coli* C3000 host bacteria. After mixing, the sample is poured onto 1.5% TSA plates and incubated overnight. Ideally, any F-RNA coliphages present will infect the host cells, replicate, and lyse the host cells (cause them to burst), expelling forth new F-RNA coliphages. The number of lysis zones, or plaques, present for each sample are summed and expressed as plaque forming units (PFU/100 mL) (Method 1602, 2001). This method was used for this thesis to evaluate the ability of ceramic candle filters to remove viruses.

During the course of this research, the brand of ceramic candle filter that possessed the greatest bacterial removal efficiency was evaluated for its ability to remove F-RNA coliphages. Although most ceramic candle filters possess a pore size of 0.2 μm or greater, and F-RNA coliphages have a diameter of 0.025 μm, most viruses and other microbes are present in the environment in clumps or aggregates (Managing Water, 2004). Pathogens may clump to one another or to other suspended particles (e.g. organic carbon) in natural waters. For this reason, removal of viruses by filtration is often greater than expected because the clumps of viruses are larger than filter pore size.

2.3 Water Quantity and Quality Standards

In this research, flow rate, turbidity removal, bacterial (total coliform and *E. coli*) removal, and viral (coliphage) removal will be determined for the AquaMaster, Doulton Super Sterasyl, Stefani São João, Pelikan, and Pozzani candle filters. The characteristics of filtered water will be compared to the U.S. EPA Standards for Drinking Water and the World Health Organization's Drinking Water Guidelines in order to determine filter efficacy.

2.3.1 U.S. Environmental Protection Agency's Primary Drinking Water Standards

The turbidity readings and microbiological concentrations of filtered water will be compared to USEPA National Primary Drinking Water Regulations to determine filter efficacy. According to the USEPA, the turbidity of treated water should not exceed 1 nephelometric turbidity unit (NTU), and 95% of daily treated water samples tested must be less than or equal to 0.3 NTU (USEPA, 2005). The maximum contaminant level goal (MCLG) for total coliforms in a water sample is 0 CFU/L. However, the enforceable standard, or maximum contaminant level (MCL) for total coliforms in a water sample requires that no more than 5% of total water sampled monthly test positive for total coliforms. Additionally, the USEPA enforces 99.99% removal or inactivation of enteric viruses. These requirements are summarized in Table 2.1.

Table 2.1: Excerpt from USEPA Drinking Water Contaminants and MCLs

Contaminant	MCLG (mg/L)	MCL or TT (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
Total Coliforms (including fecal coliform and *E. Coli*)	zero	5.0%[4]	Not a health threat in itself; it is used to indicate whether other potentially harmful bacteria may be present[5]	Coliforms are naturally present in the environment; as well as feces; fecal coliforms and *E. coli* only come from human and animal fecal waste.
Turbidity	n/a	TT[3]	Turbidity is a measure of the cloudiness of water. It is used to indicate water quality and filtration effectiveness (e.g., whether disease-causing organisms are present). Higher turbidity levels are often associated with higher levels of disease-causing microorganisms such as viruses, parasites and some bacteria. These organisms can cause symptoms such as nausea, cramps, diarrhea, and associated headaches.	Soil runoff
Viruses (enteric)	zero	TT[3]	Gastrointestinal illness (e.g., diarrhea, vomiting, cramps)	Human and animal fecal waste

Notes:

[3] EPA's surface water treatment rules require systems using surface water or ground water under the direct influence of surface water to (1) disinfect their water, and (2) filter their water or meet criteria for avoiding filtration so that the following contaminants are controlled at the following levels:

- Viruses: 99.99% removal/inactivation
-
- Turbidity: At no time can turbidity (cloudiness of water) go above 5 nephelolometric turbidity units (NTU); systems that filter must ensure that the turbidity go no higher than 1 NTU (0.5 NTU for conventional or direct filtration) in at least 95% of the daily samples in any month. As of January 1, 2002, turbidity may never exceed 1 NTU, and must not exceed 0.3 NTU in 95% of daily samples in any month.

[4] more than 5.0% samples total coliform-positive in a month. (For water systems that collect fewer than 40 routine samples per month, no more than one sample can be total coliform-positive per month.) Every sample that has total coliform must be analyzed for either fecal coliforms or *E. coli* if two consecutive TC-positive samples, and one is also positive for *E.coli* fecal coliforms, system has an acute MCL violation.

Adapted from USEPA, 2005

2.3.2 World Health Organization's Drinking Water Guidelines

Similar to the EPA's drinking water standards, WHO has established recommended guidelines for drinking water quality. In their most recent (3rd) edition of *Guidelines for Drinking Water Quality*, WHO recommends that median turbidity "be below 0.1 NTU for effective disinfection" to occur (WHO, 2004). Additionally, WHO states that drinking water should contain no indicator organisms, such as total coliform, *E. coli*, or F-RNA coliphages (WHO, 2004). However, it should be noted that in this edition (3rd) WHO states that "neither the minimum safe practices nor the numeric guideline values are mandatory limits. In order to define such limits, it is necessary to consider the guidelines in the context of the local or national environmental, social, economic and cultural conditions (WHO, 2004)." Thus, while experimentally obtained values will be compared to WHO recommended values in this thesis, failure to meet these guidelines is not necessarily indicative of a failure in treatment methods.

WHO also supports the notion that 7.5 L of water is the minimum necessary volume of water required per person per day for both consumption and food preparation purposes (Howard, 2004). The determined flow rates of the studied filters will be compared to this value to see if the filters are capable of providing enough drinking water daily.

3. Ceramic Water Filtration

3.1 Ceramic Water Filters

Ceramic water filtration is a popular method of treating contaminated water at the household level (Dies, 2003). Ceramic filters come in a variety of shapes and sizes, including hollow candle filters, disk filters, and pot filters; and can be composed of a variety of materials, such as clay or diatomaceous earth. Clay is a powdery material that forms from the wearing down of rocks containing aluminous compounds (Die Dictionary, 2005). Clay also contains many chemical impurities, which give it certain characteristics. For example, white kaolin is composed mainly of aluminum and silicate, while iron (III) oxide gives red clay its color. Black clay possesses iron (II) oxide. Calcium and magnesium are also typical compounds found in clay. Diatomaceous earth is composed of the crushed remains of tiny marine organisms called diatoms; the main components of this substance are oxygen and silicon (Environmental Chemistry, 2005).

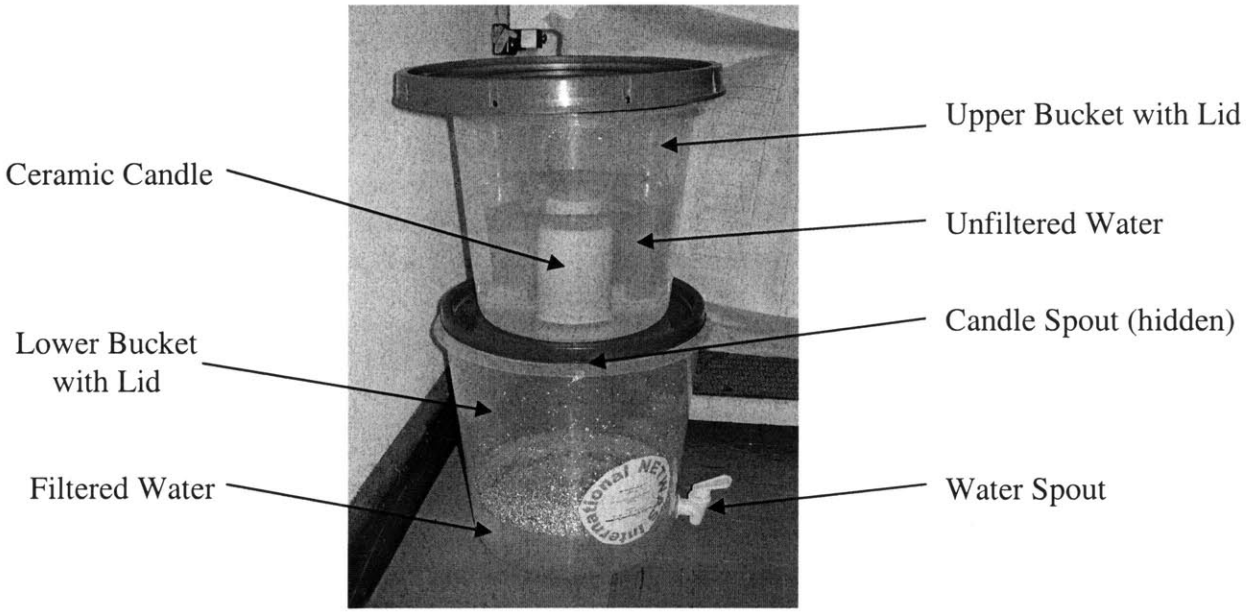


Figure 3.1: Schematic of Ceramic Candle Filter with Bucket Setup

Ceramic water filters are made by mixing clay with some combustible material, such as sawdust, flour, etc. The filter is then fired at temperatures ranging from 1000 to 3000 °C and the combustible material disappears, leaving pores in the clay (porosity). These pores form channels that allow for water to move through the filter. By adjusting clay type, combustible material, firing temperature, and filter shape, a multitude of filters can be created, each of which possesses unique properties for water purification.

3.1.1 Factors Affecting Filter Performance

Several factors can affect filter performance. These factors can be properties of the filter, such as porosity, filter thickness, or filter surface area. Factors affecting filter performance can also be characteristics of the water being filtered, such as height of water above the filter element or water quality. Additionally, filter additives, such as activated carbon and silver, can affect filter performance.

3.1.1.1 Porosity

Porosity is a critical factor affecting filter performance. Porosity is a measure of the volume of empty space, or pores, in a medium. Total porosity of a solid is defined as the volume of voids divided by the total volume of the solid (Harvey notes, 2004). Porosity in a ceramic water filter allows for water to flow through the element. Filters with a greater porosity will allow more water to flow through the filter, holding other variables constant. The size of the pores is also important in determining the level of water purification achieved. Many ceramic water filters have pores ranging in size from 0.1 to 10 microns. Filters with larger pores will not be as effective at straining/removing turbidity or microbiological contamination from a water sample. However, the flow rates of these filters will typically be greater since there is more space for water to flow through. Conversely, filters with small pores will be better at reducing turbidity and microbiological contamination, but may have very slow flow rates.

3.1.1.2 Filter Thickness

The thickness of the ceramic water filter will also affect the flow of water through the element. Filters with thin shells will allow water to flow through the element faster (greater flow rate), holding other variables constant. However, thin filters may not be as effective as thick filters at removing turbidity and microbiological contamination. Thick filters have more opportunity for particles to become trapped (greater tortuousity).

3.1.1.3 Filter Surface Area

Filter surface area is also an important factor affecting filter performance. Filter surface area is directly proportional to flow rate. Holding all other variables constant, filters with a larger surface area will have a greater flow rate, as there is more space for water to flow through. Conversely, filters with small surface areas will have slower flow rates. One way to increase surface area without modifying the filters themselves is to place multiple filters in a container. This modification works particularly well with ceramic candle filters. Rather than placing only one ceramic candle filter in a container (as in Figure 3.1), two, three, or even four candles could be placed in a bucket to increase the volume of water filtered in a given time period.

3.1.1.4 Water Elevation

In addition to filter properties, characteristics of the water will also affect the flow through the filter element. Height of water above the filter element, also known as fluid pressure or hydraulic head, will affect flow rate. The greater the height/volume of water, the more pressure on the filter

element, and thus the more flow through the pores in a given time period. As the water level declines over time (i.e. as water is filtered), the flow rate will concomitantly decrease. For this reason, the water level should be maintained as high above the filter as possible; the top bucket containing the filter should be filled continuously. It should be noted that the aforementioned factors (Sections 3.1.1.1 to 3.1.1.4) can all be related to flow rate using Darcy's Law. For a more detailed explanation of Darcy's Law, see Appendix A.

3.1.1.5 Water Quality

Water quality will also affect the flow of water through a ceramic water filter. Water possessing many suspended particles (high turbidity) and/or high organic content will not flow through the filter as quickly as cleaner water, resulting in a smaller volume of water filtered over a given time period. Polluted water will oftentimes clog the filter, resulting in the need for more frequent cleaning of the filter element. For highly turbid waters, sedimentation or coagulation can be used pre-filtration to remove large particles, thus allowing for an increase in flow rate.

3.1.1.6 Activated Carbon

In addition to evaluating flow through a ceramic water filter, other filter performance characteristics should be considered, such as the filter's ability to reduce chemical content or improve taste and/or odor (Ceramic Water Filter Technologies, 2004). To improve performance with regard to chemical, taste and/or odor removal, activated carbon is often added to the filter's interior. Activated carbon is made from "a variety of carbonaceous raw materials," which are heated slowly in the absence of air to produce an extremely porous chemically active material (Viessman et. al, 2005). The macro and micropores generated in this process are chemically active in that they adsorb organics and other chemicals. However, the pores also offer an attractive breeding ground to bacteria.

3.1.1.7 Silver

Many ceramic water filters also possess loose silver, colloidal silver, or silver nitrate on the interior or exterior of the filter element. Silver is purported to have bactericidal properties. It has been used throughout history for maintaining water cleanliness (Silver, 2005). Silver acts by disrupting the cell membrane, causing it to disintegrate. Additionally, bacteria do not develop resistance to silver, as they do for antibiotics (Pan American, 2005). Because of this, silver has become an increasingly popular additive to ceramic water filters; it is seen in such brands as AquaMaster, Doulton, and Pozzani.

3.2 Previous Engineering Studies on Ceramic Water Filters

Multiple studies have been performed on ceramic water filters. Among others, MIT Master of Engineering (MEng) students from previous years have contributed to ceramic water filter research. In this section, some of the more relevant studies to the topic of this thesis are summarized.

3.2.1 Study of Filtration for Point-of-Use Drinking Water in Nepal

In January of 2000, MIT MEng student Junko Sagara performed a study in Nepal on the Nepalese ceramic candle filter and the Indian ceramic candle filter, among others. Sagara tested each filter for turbidity removal, flow rate, and microbial removal efficiencies. Specifically, Sagara used the presence/absence (P/A) test for total coliforms and *E. coli*, and the most probable number (MPN) test for hydrogen sulfide-producing bacteria. Sagara found that none of the filters removed adequate amounts of bacteria. In an attempt to improve the microbial removal efficiencies of the filters, Sagara applied colloidal silver, a known germicide, to the surface of the filters. Sagara found that when more than 10 mg of colloidal silver (per candle) was used, all of the hydrogen sulfide-producing bacteria were removed. *Escherichia coli* bacteria were also removed by the two filters possessing the highest concentrations (13.6 and 15.3 mg) of colloidal silver. However, total coliform bacteria were not removed by the colloidal silver-treated filters. Sagara also documented the flow rate of each filter. The Nepalese ceramic candle filter had a flow rate of 0.24 L/hour, and the Indian ceramic candle filter had a flow rate of 0.3 L/hour. Additionally, all of the filters reduced the average turbidity of raw water (12 NTU) to turbidity values below 1 NTU, which is well below the year 2000 WHO guideline of 5 NTU. From her studies, Sagara concluded that the Nepalese ceramic candle filter was the most affordable filter tested, and that when used in conjunction with disinfection, it provided a suitable mode of water purification for individual households (Sagara, 2000).

3.2.2 Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter

In 2001, MIT MEng graduate Danielle Lantagne conducted a study of the Potters for Peace (PFP) Colloidal Silver Impregnated Ceramic Filter post-graduation. In her study, Danielle performed a survey of families in Nicaragua possessing a PFP filter. Lantagne found that when used properly, the filter could remove 100% of indicator bacteria. However, due to receptacle contamination and inadequate water storage, only 4% of the household filters removed total coliform, with 25% removing H_2S-producing bacteria, and 53% removing *E. coli*. Lantagne also studied MS2-coliphage (a.k.a. F-RNA coliphages) removal by the filters, and found that there was only an 18.7% reduction in coliphage numbers post-filtration. This was blamed on the 0.6-3 micron pore size of the filter, which would not likely remove 0.02 micron coliphages (Lantagne, 2001).

3.2.3 Appropriate Microbial Indicator Tests for Drinking Water in Developing Countries and Assessment of Ceramic Water Filters

In January of 2002, MIT MEng student Chian Siong Low worked with Mr. Hari Govinda Prajapati of Thimi, Nepal to develop a ceramic disk filter (Thimi filter). Low subjected this filter, as well as the TERAFIL Indian terracotta ceramic filter, to tests for turbidity removal, flow rate, and microbial removal efficiencies. Low found that the TERAFIL filters had a faster flow rate than the Thimi filters. For the most part, all filters reduced turbidity by at least 85%. Low also found that the TERAFIL filter tested at MIT had a 94-99.99% removal efficiency of total coliform, while the TERAFIL filter tested in Nepal had an 80-100% removal efficiency of fecal coliform and an 80-99.89% removal efficiency of *E. coli*. Low's Thimi filters had total coliform removal rates of 89-99.69%, *E. coli* removal rates of 96-100%, and a fecal coliform removal rate of 100%. Low tested the filters with a 0.0027% solution of colloidal silver, but concluded that this substance had no

noticeable effect on coliform removal rates at this concentration. In order to remove 100% of the bacteria, Low suggested the use of a disinfection process in addition to filtration, such as chlorine disinfection or SODIS (solar disinfection) (Low, 2002).

3.2.4 A Feasibility Study to Assess the Potential for Red Clay Ceramic Water Filters to be Reproduced by Skilled Artisans and an Evaluation of the Filter's Ability to Remove Protozoa, Bacteria, And Virus Pathogens

During the 2002-2003 academic year, Cranfield University at Silsoe Master of Science student Stuart Cheesman examined the potential for local artisans to make red clay ceramic water filters, while also testing the ability of the filters to remove pathogens from drinking water. In his study, Cheesman used fluorescent microspheres (which mimic *cryptosporidium* oocysts), thermotolerant coliforms (TTC), and T_4 bacteriophages to gauge the filters' abilities to remove protozoa, bacteria, and viruses, respectively, from solution. It should be noted that Cheesman applied a 200 ppm solution of colloidal silver to each of the filter elements. All filters constructed showed 100% removal of microspheres (protozoa mimic) and at least a 99.7% removal of TTC. Unfortunately, the filters did not appear to be effective at removing viruses from solution; raw water and filtered water T_4 bacteriophage concentrations were comparable (Cheesman, 2003).

3.2.5 Development of a Ceramic Water Filter for Nepal

In 2003, MIT MEng student Robert Dies evaluated three types of ceramic disk filters and five types of candle filters for flow rate and microbial removal efficiency. Dies found that of the eight filter types tested, the red-clay grog disk filter, Katadyn® Ceradyn candle filter, Katadyn® Gravidyn candle filter, and Hari Govinda white-clay candle filter had microbial removal efficiencies over 98% when coated with colloidal silver and flow rates ranging from 0.641 L/hour to 0.844 L/hour (Dies, 2003). Dies used membrane filtration and m-ColiBlue24 broth for his microbial analysis. The results of Dies' study support the use of colloidal silver as a bactericide. Dies also performed extensive research on the ceramic filter production process and methods of bringing low cost filters to market in Nepal (Dies, 2003).

3.2.6 Six Month Field Monitoring of Point-of-Use Ceramic Water Filter by Using H_2S Paper Strip Most Probable Number Method in San Francisco Libre, Nicaragua

In 2003, MIT MEng student Rebeca Eun Young Hwang developed a monitoring program in San Francisco Libre, Nicaragua to evaluate the Potters for Peace (PFP) ceramic water filter. The PFP "Filtron" is a pot shaped filtering element composed of terracotta clay, as opposed to the white clays used in many ceramic candle filters. In her study, Hwang examined the flow rate, microbial removal efficiency, and user acceptance of 100 PFP filters. Hwang found that the average flow rate of the PFP filter was 1.7 L/hr. To test for bacterial removal efficiency, Hwang utilized the Hydrogen Sulfide Paper Strip Most Probable Number Test and the Membrane Filtration Test with m-ColiBlue24 broth. Her results show that 80.4% of the filtered samples possessed less than 2.2 H_2S-producing colonies per 100 mL. Removal rates for E. coli and total coliform were found to be 97.6% and 89.3% respectively. A follow-up study performed by Teresa Yamana suggested that Hwang's PFP pilot study may have overrated the coliform removal efficiency of the filters (Yamana, 2004). Hwang also attempted to determine user

acceptance by employing a household survey. Responses revealed that people were not satisfied with the small filter capacity (20 L). Hwang recommended that bigger filters be manufactured to meet the demand for increased volume and to increase the flow rate. Hwang also found that 15% of the filters broke over the six-month study period, revealing a design flaw. Hwang deduced that a reduction in breakage rate must occur if the PFP filter is to serve as a viable and consistent source of household water treatment (Hwang, 2003).

3.2.7 Evaluation of Point-of-Use Microfiltration for Drinking Water Treatment in Rural Bolivia

In 2003, University of Cambridge doctoral student Joe Brown conducted a 25-week trial study examining the field effectiveness and sustainability of point-of-use (POU) ceramic candle filtration units in Charinco, Bolivia. For this study, Brown utilized two silver-impregnated Ceradyn™ candle filters (manufactured by Katadyn®) per household unit. Before distributing the filtration units to 25 households in the community, Brown performed sampling of the households' water. He returned to the households for sampling at weeks 7, 13, 20, and 25. Relating to filter performance in the field, Brown discovered that the Ceradyn™ filter units were capable of consistently reducing the thermotolerant coliform (TTC) concentration in raw water (488-4220 TTC/100 mL) down to 0 TTC/100 mL. However, water sampled from households possessing filters showed turbidities similar to baseline levels (27.6 NTU). It should be mentioned that turbidity determinations utilized the DelAgua method, which may have skewed results. Additionally, Brown found that the maximum observed flow rate per unit (two filters) was only 1 L/hr. Brown also witnessed a 32% failure rate among the filters (due to breakage) during his trial study. Nonetheless, Brown concluded that ceramic candle filtration is a promising technology for providing clean water to the people of Charinco (Brown, 2003).

3.2.8 An Evaluation of Household Drinking Water Treatment Systems in Peru: The Table Filter and the Safe Water System

In 2004, MIT MEng student Brittany Coulbert traveled to Peru to assess a household water treatment program implemented by the Pan American Center for Sanitary Engineering and Environmental Sciences (CEPIS) and Peru's Ministry of Health. The two systems implemented in Peru were the Table Filter and the Safe Water System. The Table Filter is composed of a geotextile cloth pre-filter and two Pozzani ceramic candle filters. The Table Filter system showed 99% removal of *E. coli*, 98% removal of total coliform, and 67% removal of turbidity. Table Filters possessing either medium or fine grain sand were also tested back at MIT. The Medium Sand Table Filter possessed a 98% thermotolerant coliform removal efficiency and a 91% turbidity removal efficiency. The Fine Sand Table Filter showed similar thermotolerant coliform removal results, but possessed a 92% turbidity removal. Studies using Pozzani candles alone show the isolated candles to possess a slower flow rate than the complete Table Filter system. Coulbert concluded that filtration followed by household disinfection would be the most effective water treatment method (Coulbert, 2005).

3.2.9 Water Disinfection in Ceramic Filters Impregnated with Colloidal Silver

In spring of 2005, four MIT students in the Department of Materials Science and Engineering, Anna Bershteyn, Sheldon Hewlett, Jacob Myerson, and Sarah Ng, worked on a project to develop an improved ceramic pot filter to be used for disinfection of drinking water. Their research included characterizing the pore size of various filters; three of which were ceramic candles: the Katadyn filter, Pelikan filter, and Doulton Super Sterasyl filter. Results from their studies revealed that the Katadyn filter has a tortuosity of 1.7 and a total porosity of 15.9%. The pore sizes found in the Katadyn ranged from 0.1-10 μm. The Pelikan filter was found to have a tortuosity of 1.9 and a total porosity of 76.7%, with pore sizes ranging from 0.1 to 10 μm; the majority of pores in this filter possessed a size of 0.1 to 1 μm. The Doulton Super Sterasyl was found to have a tortuosity of 2.2 and a total porosity of 32.5%. With regard to pore size, the Doulton also showed a range of 0.1 to 10 μm (Bershteyn et al.). Graphs of pore size distribution for the Katadyn, Pelikan, and Doulton Super Sterasyl ceramic candle filters are provided in Appendix B.

3.2.10 Summary of Literature Review

The results obtained from the aforementioned ceramic candle filter studies are summarized in Table 3.1.

Table 3.1: Summary Table of Ceramic Candle Filter Studies

Filter	Date	Reference	Pore Size (microns)	Flow Rate (L/hr)	Percent Turbidity Removed (source (NTU))	Percent Removal of: TC (raw water concentration (CFU/100 mL))	Percent Removal of: TTC (raw water concentration (CFU/100 mL))	Percent Removal of: *E. coli* (raw water concentration (CFU/100 mL))	Colloidal Silver (CS) Added?	Notes
Nepalese Ceramic Candle Filter	2000	Sagara		0.24	96.2%, (12)	P/A Test used; TC not removed when coated or not with CS		P/A Test used; *E. coli* removed when coated with CS	Yes	It should be noted that TC and *E. coli* results included in this section are for filters coated with 13.6 mg and 15.3 mg colloidal silver (uncoated removed no bacteria)
Indian Ceramic Candle Filter	2000	Sagara		0.3	94.3%, (12)				Yes	
Red Clay Ceramic Candle	2003	Cheesman		0.124			99.9% (230-1700)		Yes	TTC results are for filters coated with CS only. Uncoated filters showed >93.5% removal.
Katadyn Ceradyn Ceramic Candle	2003 2005^	Dies Brown*	0.1-10^ [Bershteyn]	0.641 < 0.5*	No sig. reduction (27.6)*	> 98%, (89)	100% (488-4220)*	> 98% (56)	No	Note that data is compiled from two separate studies; Brown's results designated with *.
Katadyn Gravidyn Ceramic Candle	2003	Dies		0.844		> 98%, (89)		> 98% (56)	No	
White Clay Ceramic Candle Filter	2003	Dies		CS: 0.678 None: 0.742		CS: > 98%, (89) None: 84% (89)		CS: > 98% (56) None: 88% (56)	Yes No	Note that top values are for filter coated with CS and bottom values are for uncoated filter.
Hong Phuc Ceramic Candle	2003	Dies		0.3		85% (89)		> 98% (56)	No	
Pozzani Candle Filter	2005	Coulbert		2.05	88% (19)	99.8% (50000)	97% (1900)	99.8% (890)	No	Note that data is taken from studies performed on filters once covered with Fine Sand.
Pelikan	2005	Bershteyn	0.1-10, most in 0.1-1 range							
Doulton Super Sterasyl	2005	Bershteyn	0.1-10							

3.3 Ceramic Candle Filters Studied

During the course of this research, several different types of ceramic candle filters were examined. In this thesis, the AquaMaster (Piedra Candle), Doulton Super Sterasyl, Pelikan, Pozzani, and Stefani São João candle filters were compared based on cost, flow rate, turbidity removal, and microbial removal. The AquaMaster (Piedra Candle) and Pelikan filters were selected because they were locally available at Kenyan markets such as the Nakumatt market and Yaya Center. The Stefani São João was selected because it was available through the Network for Water and Sanitation in Kenya (NETWAS Kenya) (see Baffrey, 2005). Additionally, NETWAS Kenya was distributing Doulton Super Sterasyl filters in various households in Kenya. Because of this, the Doulton Super Sterasyl was selected for testing. Finally, the Pozzani filter was included in the testing because it was a low cost filter that is available worldwide. This filter was also studied by past MEng student, Brittany Coulbert (Coulbert, 2005).

3.3.1 AquaMaster (Piedra Candle)

The AquaMaster (Piedra candle) is a white clay filter manufactured in Brazil, and contains carbon and silver nitrate. This candle element was purchased locally in Nairobi, Kenya at the Nakumatt market for 795 Ksh ($10)[2]. The candle has a length of approximately 10 cm and a diameter of about 5.4 cm.

3.3.2 Doulton Super Sterasyl

The Doulton Super Sterasyl candle is manufactured by Fairey Industrial Ceramics Ltd in the UK (Water Filter Information). This 10 inch (25.4 cm) by 2 inch (5.1 cm) candle is composed of diatomaceous earth with silver and loose carbon located in the interior. According to the manufacturer, the Super Sterasyl filter has a 99.99% particulate filtration efficiency for particles down to 0.9 micron in diameter. For particles ranging in size from 0.5 to 0.8 micron, the particulate removal efficiency is 99.9%. This filter also boasts a 99.99% removal efficiency of *E. coli*. It is recommended that this filter be replaced after six months; it can filter a capacity of 2,000 liters (535 gallons) before needing replacement (Fairey, 2005). This filter is purported to have a flow rate of up to 1.34 L/hr (Ecobest, 2005). Although it is not NSF (National Sanitation Foundation) certified, this filter is WRAS (Water Regulations Advisory Scheme) approved. The Doulton Super Sterasyl candle currently retails for $39.95 in the U.S.

[2] Exchange Rate: US $1.00 = Ksh 76

Figure 3.2: Doulton Super Sterasyl Candle Filter

3.3.3 Stefani São João

The Stefani São João is a white clay candle filter manufactured in São Paulo, Brazil by Cerâmica Stéfani (Cerâmica Stéfani, 2005). This filter possesses activated carbon and has a length of 10 cm and a diameter of 6 cm. The Stefani São João is advertised as a dechlorinating filter; the activated carbon is purported to remove such chemicals as chlorine, iron, lead, manganese, aluminum, etc. In South America, this filter retails for about $1.50-$3.00.

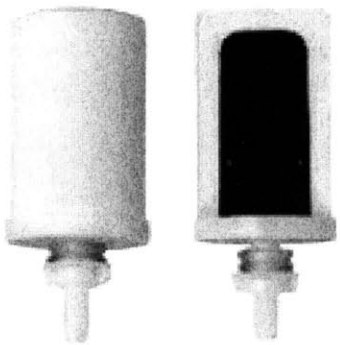


Figure 3.3: Stefani São João Candle Filter

3.3.4 Pelikan

The Pelikan is a white clay ceramic candle filter manufactured in India. This filter element was purchased in Nairobi, Kenya at the Nakumatt market for 130 Ksh ($1.70). This filter was also available at the Yaya center for a price of 250 Ksh ($3.30). The Pelikan filter has a length of approximately 19.7 cm and a diameter of 5.4 cm.

3.3.5 Pozzani

The Pozzani is a white clay ceramic candle filter that is manufactured in Brazil by Pozzani Industria Cor & Design. This filter element is sold in many countries around the world (Pozzani). The filter element contains silver nitrate and possesses a length of 10 cm and a diameter of 5.6 cm.

3.3.6 Filter Characteristics

Table 3.2 summarizes the characteristics of the studied filters, as provided by the manufacturers.

Table 3.2: Filter Characteristics

Filter	Origin	Cost of Filter ($)	Carbon	Silver	Height of Filter (cm)	Diameter of Filter (cm)	Percent *E.coli* Removal
AquaMaster	Brazil	10	Yes	Yes	10	5.4	not stated
Doulton	UK	40	Yes	Yes	25.4	5.1	99.99%
Stefani	Brazil	2.25	Yes	No	10	6	not stated
Pelikan	India	2	No	No	19.7	5.4	not stated
Pozzani	Brazil	20	No	Yes	10	5.6	not stated

4. Tests on Ceramic Candle Filters

4.1 Research Objective

The goal of this research is to assess the performance of ceramic candle filters that are locally available in Kenya. These filters will be evaluated based on the following parameters: flow rate, turbidity removal, bacterial removal, and cost. The brand of filter that performs the best at removing bacteria will also be tested for viral removal. Results from this study will lead to recommendations regarding the best-performing ceramic candle filter(s).

4.2 Study Design

In January of 2005, the author traveled to Kenya to test five different brands of ceramic candle filters for the aforementioned parameters. Research was conducted at the Ministry of Water Resources Management and Development's Pollution Control Division in Nairobi. The filters studied were the AquaMaster (Piedra candle), Doulton Super Sterasyl, Stefani São João, Pelikan, and Pozzani candles. Two filters of each of these brands were tested, resulting in a total of ten filters tested. Contaminated water used in testing was obtained from a nearby polluted river within Nairobi. This polluted source was selected for several reasons. First of all, several different agencies, such as the Environmental Protection Agency (EPA) and NSF International, seek 10^4, 10^5, and 10^6-fold values of bacterial removal. This extent of bacterial removal can only be demonstrated if high raw water (influent) bacterial concentrations are used. Secondly, MIT students traveling to rural areas in Kenya observed the use of highly contaminated surface waters as sources of drinking water in a number of instances.

Before running it through the filters, the contaminated water source was diluted 1:10 or 1:100 with tap water (see Appendix C for characteristics) in order to reduce the volume of source water that needed to be transported to the lab. Tests enumerating total coliforms and *E. coli* were performed on filtered and unfiltered water to determine bacterial removal efficiencies for each of the filters. Tests for flow rate and turbidity removal were also performed using the diluted, highly contaminated water.

Upon returning to MIT, the author continued water quality testing and performance testing of the above ceramic candle filters during the months of February and March. The same filters tested in Kenya were examined at MIT, with one exception. On the way back, one of the Pelikan filters studied in Kenya broke. This filter was replaced with a new Pelikan, which was subjected to tests at MIT. Filter tests performed at MIT utilized undiluted Charles River water, which is significantly less polluted (1.4×10^3 to 6.1×10^3 CFU total coliform/100 mL) then the water used in Kenya (7.8×10^4 to 1.6×10^6 CFU total coliform/100 mL). At MIT, filters were tested further for bacterial removal, turbidity removal, and flow rate.

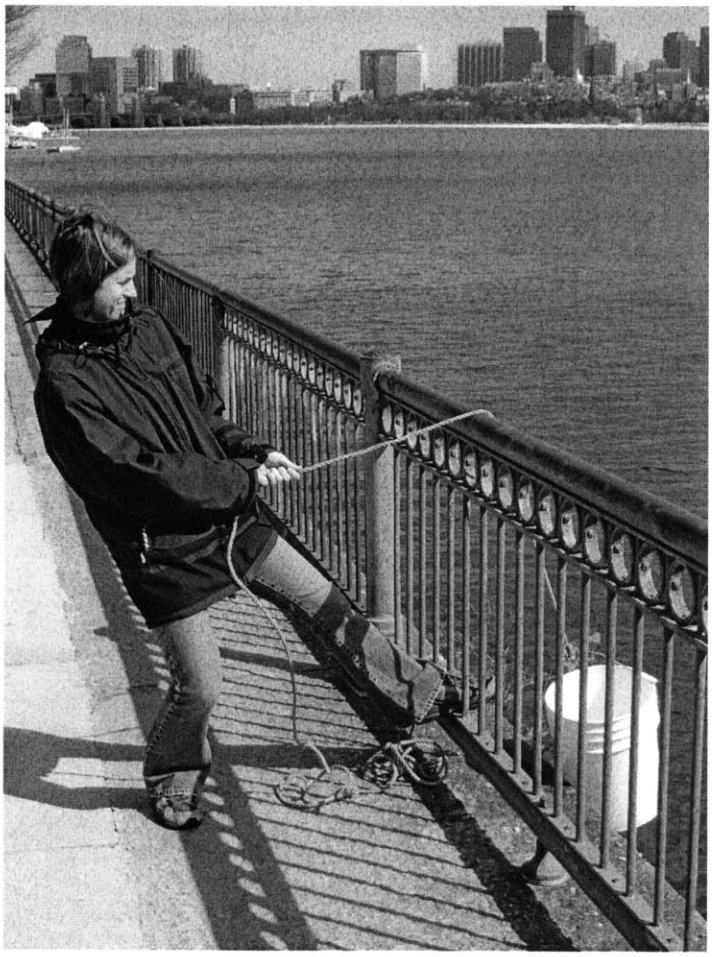


Figure 4.1: Collecting Water from the Charles River

After determining the filters most effective at removing bacterial contamination, tests for viral removal were performed in the months of March and April, 2005 at MIT.

4.3 Methodology

Upon arriving in Kenya, filters not already obtained were purchased at local markets in Nairobi. The AquaMaster (Piedra candle) and Pelikan filters were purchased at the Nakumatt market on Ngong Road in Nairobi for 795 Ksh ($10) and 130 Ksh ($2) respectively. The Stefani São João was generously donated by NETWAS, a local non-governmental organization (NGO). The Doulton Super Sterasyl and Pozzani candles were obtained in the U.S. The Doulton was chosen for this study because this brand of filter is being distributed to Kenyan locals by NETWAS, as part of a project to determine the social acceptability of this product. See Baffrey, 2005 thesis for more information on NETWAS's Doulton project. Finally, the Pozzani candle filters were selected for comparative reasons. This filter is available throughout the world and was tested by former Master of Engineering student Brittany Coulbert (Coulbert, 2005).

Other materials, such as buckets and wooden planks, were also purchased in Nairobi. Buckets with lids were purchased at the Nakumatt Market for 165 Ksh a piece ($2). Wooden planks were

obtained from a lumberyard in Nairobi through the husband of a Ministry of Water Pollution Control lab member. The Ministry of Water Pollution Control Unit allowed access to their laboratory equipment and also provided some of the supplies for this research. The rest of the equipment and supplies were provided by MIT and were brought to Kenya from the U.S. A list of materials that were essential to this research project that were bought/available in Nairobi follows.

Materials Purchased in Nairobi

- Two wooden planks
- Twelve 16-L buckets with lids
- Two drill bits for burning holes (31/64 and 15/32 inch diameters)

Materials Provided by Water Pollution Control Unit

- Bunsen burner
- Jerry cans for collecting water samples
- Beakers for collecting water for flow rate tests (500-mL and 1-L)
- Freezer for chilling ice packs
- Ethanol
- Methanol
- Four Graduated cylinders (100 mL)
- Tap water (see Appendix C)
- Distilled water
- Termaks type B 2221 V Incubator: Bergen, Norway (37°C)

In addition to the aforementioned materials, supplies were brought to Kenya from the U.S. For a complete list of these supplies see Appendix D.

After obtaining the necessary supplies, the filter units were set up. Holes were burned in half of the buckets using a large drill bit (31/64 or 15/32 inch diameters) that was heated using a Bunsen burner. An Exacto knife was used to smooth the holes. These upper buckets were used to house the filters, while the remaining lower buckets were used to collect water dripping out of the filters (See Figure 4.2). Filters were inserted into the holes and screwed in, with rubber gaskets placed on either side of the bucket to form a tight seal (and prevent leakage). The upper buckets with ceramic candle filters were then placed on two parallel wooden planks, which were supported on either end by chairs (Kenya) or sand-filled buckets (MIT). The planks were spaced a few inches apart so that the buckets could rest on them with the spout of the filter being unobstructed. Buckets (without holes) were then placed beneath each of the buckets with filters to collect filtered water.

Figure 4.2: Filter Setup in Kenya

Figure 4.3: Filter Setup at MIT

Each candle filter was evaluated for flow rate, turbidity removal, and bacterial removal. In Kenya, initial and final flow rate tests were performed on each filter for each run of diluted, highly contaminated water. At MIT, only one flow rate test was performed for each run of Charles River water. Turbidity tests were performed in triplicate on filtered water collected from each flow rate test. These turbidity readings were compared to turbidity readings for unfiltered water to determine percent turbidity removal. Membrane filtration (MF) was used to detect and enumerate total coliforms and *E. coli* in filtered and unfiltered samples. For each water sample, duplicate tests were performed. All data at MIT was subjected to statistical analysis. The statistical t-test was used to determine the probability that the data obtained for each filter was significantly similar or different for each combination of filters (using a 95% confidence interval) [See Appendix E].

Before performing the initial tests in Kenya and at MIT, tap water was allowed to pass through the filters overnight to saturate the element. If blockage occurred, filters were gently scrubbed using steel wool and tepid water. All filters were cleaned in this manner before leaving Kenya and upon returning to MIT (except the new Pelikan). This was done in an effort to remove any residual gunk remaining on the filters from Nairobi.

4.3.1 Turbidity Tests

Turbidity tests were performed on water samples collected during flow rate tests. Turbidity relates to the presence of suspended particles present in water and is a measure of the interference of light caused by these particles. In this study, turbidity values are reported as nephelometric turbidity units (NTU). Turbidity measurements were made using the Hach 2100P turbidimeter. Water samples were placed in clear glass vials, which were then inserted into the turbidimeter with a consistent orientation. Turbidity tests were performed in triplicate for each water sample. Blanks were also performed in triplicate for each group of turbidity tests, the average of which was subtracted from the average turbidity value for each sample.

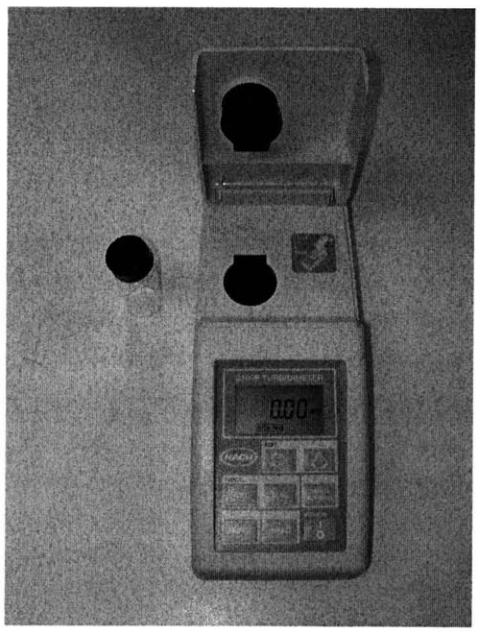


Figure 4.4: Hach 2100P Turbidimeter and Glass Vial

In Kenya, initial and final turbidity tests were performed in triplicate for two runs of filter testing. Initial tests were performed several hours after first submerging the ceramic candle filter element in polluted water. Final tests were performed approximately 20 hours after submerging the ceramic candle filter element in polluted water. Filtered water turbidity readings were compared to unfiltered source water readings to determine turbidity removal by the studied filters.

At MIT, turbidity tests were performed in triplicate for nine runs of filter testing. Turbidity tests were performed several hours after submerging the ceramic candle filter element in polluted water. Filtered water turbidity readings were compared to unfiltered source water readings to determine turbidity removal by the studied filters.

Turbidity removal was calculated using the following formula.

Turbidity Removal (%) = [1 – ((avg. turbidity – avg. blank turbidity)/(source turbidity))] x100

4.3.2 Flow Rate Tests

Multiple flow rate tests were performed on each filter. Contaminated source water was poured into the buckets possessing filters. The buckets were filled so that the water level was flush with the top of the filter (so different volumes were used depending on the filter height – see Table 4.1). Flow rate tests were performed by placing a beaker under the filter spout and allowing water to drip into the beaker for a specified period of time. Beakers were placed in the buckets beneath the filters so that any overflow would be caught. The volume of water filtered was then compared to the time it took for water to filter.

Table 4.1: Filter and Water Characteristics Observed at MIT

Filter	Height of Filter (cm)	Diameter of Filter (cm)	Volume of Water Used (L)	Height of Water (cm)
AquaMaster	10	5.4	3.5	11
Doulton	25.4	5.1	13.5	26
Stefani	10	6	3.5	11
Pelikan	19.7	5.4	7.5	20
Pozzani	10	5.6	3.5	11

Figure 4.5: Picture Depicting Flow Rate Test via Collection of Water in Graduated Cylinder

In Kenya, two successful runs were completed for each filter. For each of these runs, an initial and final flow rate determination was made. The initial flow rate was measured approximately three hours after adding contaminated water to the filters. Final flow rate measurements were made the next day, approximately 20 hours after first placing the polluted water in the filter-possessing buckets.

At MIT, only one flow rate test was performed per run, and a total of nine runs were performed. The reason for not performing a flow rate test after 20 hours, as was done in Kenya, related to the fact that the Charles River water was much less turbid than the Nairobi sewer water. Thus while in Nairobi there would still be highly contaminated water remaining to be filtered after one day, there would be very little left of the Charles River water after one day. In other words, the flow rate was fast enough using Charles River water to eliminate the possibility of a final (after 20 hours) flow rate test.

Flow rate was determined by dividing the volume of water filtered by the time it took for that volume to be filtered.

Flow rate (L/hr) = (volume filtered [L])/(elapsed time [hrs])

4.3.3 Membrane Filtration Test for Total Coliforms and E. coli

The membrane filtration test was used to quantify the amount of total coliforms and *E. coli* present in a sample. Duplicates for each sample of filtered water were tested and compared to dilutions of unfiltered water in an attempt to determine bacterial removal efficiencies and/or log removal of bacteria by the studied ceramic water filters. The formulas used to calculate bacterial removal efficiency and log removal are as follows.

% Removal efficiency = [1 – ((unfiltered sample – filtered sample)/unfiltered sample)] x100

Log removal of coliforms by filters = $\log_{10}$ [$(CFU/100\ mL)_{source}/(CFU/100\ mL)_{filtered}$]

In membrane filtration, a sample of water passes through a filter possessing 0.45 μm pores. Because bacteria such as *E. coli* are slightly larger than the pore size (1x3 μm), bacteria present in the water will collect on the surface of the filter (Madigan, 2002). Once filtration is complete, a nutritive broth is supplied to the filter in a petri dish. In this research, m-coliBlue24 (Hach cat. 26084-50) was used. This broth is a nutritive, lactose-based medium which contains inhibitors that prevent the growth of non-coliforms (USEPA, 2003). After incubation at 35°C ± 0.5°C for 24 hours, individual bacterial cells will have replicated, producing colonies that consist of millions of clones of the original bacterium. These colonies are visible to the human eye and are defined as colony forming units (CFUs). A selective dye present in the broth, 2,3,5-Triphenoltetrazolium Chloride (TTC), highlights total coliform colonies in red. Among these coliforms, any colonies originating from an *E. coli* bacterium are highlighted in blue via the action of the *E. coli* β -glucuronidase enzyme on 5-Bromo-4-Chloro-3-Indolyl-β-glucuronide (BCIG) (USEPA, 2003). Thus total coliform and *E. coli* colonies can be differentiated from one another through this method. Numbers of colonies detected for each sample are expressed as CFU/100 mL.

Experimental Method

The list of materials and supplies can be found in Appendix F.

Figure 4.6: Membrane Filtration Supplies

Procedure

1. Water samples were collected using Presterilized Whirl-Pak® bags. Each bag contained a thiosulfate tablet, which neutralized residual chlorine that might interfere with microbial analysis.
2. Each MF filtration unit was sterilized by adding a small volume of methanol to the lower disk. The methanol was ignited with a lighter, and the filter unit was then capped. This action produced formaldehyde, which sterilized the MF filtration unit if allowed to sit for 15 minutes. Sterilization between filter brands was performed to prevent cross-contamination.
3. Dilutions of source water (unfiltered) with distilled water were prepared in order of least to greatest concentration. Dilutions of 1:10,000, 1:100,000, and 1:1,000,000 were used for Nairobi sewer water. Dilutions of 1:100 and 1:20 were used for Charles River water.
5. For each test, sterile distilled water (100 mL) was first filtered as a blank. The hand pump was used to draw all the water through the 45 mm 0.45 μm filter, which was placed grid side up on the filter unit. Forceps were sterilized with flame from a lighter and used to remove the membrane filter. The contents of one m-ColiBlue24 2-mL ampule were added to the absorbent pad of the petri dish. After making sure the pad was completely soaked, extra broth was poured off. The membrane filter was then placed face-up in the broth-soaked petri dish using the sterilized forceps. The lid was placed on the petri dish and inverted before placing in a 35°C ± 0.5°C incubator for 24 hours.
6. This process was repeated for each sample, starting with the lowest source dilution. Filtered water samples were then tested (in duplicate). The filter unit was sterilized after running the samples for each brand of ceramic water filter.
7. After 24 hours, the petri dishes were removed from incubator. The number of red and blue colonies (red and blue = total coliform, blue = *E. coli*) were then observed and counted. The numbers of colonies were expressed as CFU/100 mL.

4.3.4 Double Agar layer Procedure for the Detection and Enumeration of F-RNA Coliphages

The double agar layer procedure, detailed in EPA Method 1602: Male-specific (F^+) and Somatic Coliphage in Water by Single Agar Layer (SAL) Procedure, will be used to quantify the amount of F-RNA coliphages present in contaminated water sources (Method 1602, 2001). This method was generously donated to the author by Douglass Wait, the lab manager of Professor Mark Sobsey's microbiology lab in the Department of Environmental Science and Engineering at UNC-CH. Joe Brown, a Ph.D. student at this laboratory, also donated his methodology notes and advice to the author. This method was selected for its clarity and ability to quantify the amount of coliphages present in a sample. Filtered water was tested and compared to unfiltered water to determine viral removal efficiencies of the Pelikan candle filters.

In this procedure, a water sample containing MS2 coliphages (strain of F-RNA coliphages) is assayed. The sample is added to molten 45°C 0.7% tryptic soy agar (TSA) containing either *E. coli* C3000 host bacteria or antibiotics and *E. coli* F_{amp} host bacteria. *E. coli* C3000 host bacteria picks up both somatic and male-specific coliphages. *E. coli* F_{amp} host bacteria picks up only male-specific coliphages. The viral-bacterial agar solution is mixed and immediately poured into plates containing a solid lower 1.5% TSA layer. After the upper agar solidifies, the plates are inverted and incubated overnight. Ideally, any MS2 coliphages present will infect the host cells, replicate,

and lyse the host cells (cause them to burst), expelling forth new coliphages. The number of lysis zones, or plaques, present for each sample are summed and expressed as plaque forming units (PFU/100 mL) (Method 1602, 2001).

Experimental Method

The list of materials and supplies can be found in Appendix G.

Reagents and Standards

Obtain or prepare the following standards several days previous to performing filter assay.

- Glycerol: autoclave for 15 minutes at 121°C and 15 psi.
- 1X Phosphate Buffered Saline (PBS): Add 4 g of NaCl, 0.1 g of KCl, 0.72 g of Na_2HPO_4, and 0.24 g of KH_2PO_4 to a 1-L and add approximately 400 mL of distilled water. Adjust pH to 7.4 using HCl. Adjust volume to 500 mL, screw cap on loosely, and autoclave for 45 minutes at 121°C and 15 psi. Refrigerate at 4°C.
- Ampicillin/streptomycin stock solution: Dissolve 0.15 g each of ampicillin sodium salt and streptomycin sulfate in 100 mL reagent water. Filter through sterile 0.22 μm pore size membrane filter assembly. Dispense 5-mL aliquots in freezer vials and freeze at -20°C.
- Tryptic Soy Broth (TSB) for growing up *E. coli* C3000: Add 15 g of tryptic soy powder per 0.5 L of distilled water in 1-L screw-top bottle. Screw cap on partially and autoclave for 15 minutes at 121°C and 15 psi. This solution can be stored in the refrigerator or at room temperature for several weeks.
- TSB plus ampicillin/streptomycin for growing up *E. coli* F_{amp}: Add 1 mL ampicillin/streptomycin (amp/strep) stock solution per 100 mL of cooled, autoclaved TSB. Mix. Note that amp/strep should be added to TSB immediately prior to use (not earlier).

Procedure

1. Several days before testing filters for viral removal, prepare the viral stock*. Note that directions for preparing log phase host, 1.5% TSA bottom plates, etc. are described in steps 2 and up. Viral stock need only be prepared once if enough is made to last for duration of filter assays.

   ****Viral stock***: Prepare 0.35% soft top agar by adding 3.5 g bacto agar per 1 L TSB. Autoclave and place in 45°C water bath. Add 1 mL log phase bacterial host/60 mL agar and swirl. Add 1 mL thawed virus stock (obtained from Joe Brown) per 60 mL agar and swirl. Immediately pour this mixture onto 1.5% TSA bottom plates until all used up. Allow to solidify. Cover plates and place them inverted in 36°C ± 1°C incubator overnight. The next day, scrape the top agar into sterile centrifuge tubes. Add chloroform to this mixture in a 1:1 ratio. Agitate vigorously for 3-5 minutes. Centrifuge for 20 minutes at 4°C at 2500 rcf. Remove top layer (aqueous) and place in sterile vial along with 20% sterile glycerol. Store viral stock at -80°C. This stock should have a viral concentration of around 10^{10}-10^{12} viruses/mL. Do an assay to determine concentration.

2. Autoclave necessary amount of 16 x 150 mm dilution tubes with screw caps, pipette tips, Eppendorf tubes, and several 250-mL Erlenmeyer flasks with cloth stoppers the day before the assay.
3. Prepare 1.5% TSA bottom layer plates at least one day before filter assay.
   - ***1.5% Tryptic soy agar (TSA) for bottom layer of plates used to grow E. coli C3000***: Prepare TSB and add 15 g agar/L TSB before autoclaving for 45 minutes. Mix well and dispense 17-18 mL per 100-mm plate. Allow agar to solidify before use, replace lids, and store inverted at 4°C ± 1°C for up to 2 weeks.
   - ***1.5% Tryptic soy agar (TSA) for bottom layer of plates used to grow E. coli F_{amp}***: Prepare TSB and add 15 g agar/L TSB before autoclaving for 45 minutes. Once solution has cooled, add 10 mL amp/strep stock solution per 1 L of 1.5% TSA. Mix well and dispense 17-18 mL per 100-mm plate. Allow agar to solidify before use, replace lids, and store inverted at 4°C ± 1°C for up to 2 weeks.
4. Prepare overnight host (1-2 days before assay depending on whether streak plate method or direct inoculation is used).
   - ***Frozen E. coli C3000 host bacteria stock culture***: Streak host bacteria onto 1.5% TSA plate (with no antibiotic) to attain isolated colonies. Incubate overnight, pick individual colony and inoculate in 25 mL TSB. Allow bacteria to grow overnight. Or scrape some of frozen host using a pipette tip and inoculate directly into 25 mL TSB.
   - ***Frozen E. coli F_{amp} host bacteria stock culture***: Streak host bacteria onto 1.5% TSA plate (with amp/strep) to attain isolated colonies. Incubate overnight, pick individual colony and inoculate in 25 mL TSB plus ampicillin/streptomycin. Allow bacteria to grow overnight. Or scrape some of frozen host using a pipette tip and inoculate directly into 25 mL TSB containing amp/strep.
5. Prepare log phase host the morning of assay.
   - ***Log phase bacteria stock***: Add 0.1-1 mL host bacteria to 25 mL TSB (plus amp/strep if using *E. coli* F_{amp}) in 125 or 250-mL shaker flask. Loosely plug flask and incubate at 36°C ± 1°C with shaking at 80-100 rpm for 1.5-2 hours. Remove 1 mL culture after 1.5 hours, place in cuvette, and use spectrophotometer to read absorbance at 520 nm (after blanking with plain TSB). If absorbance reading is less than 0.4 OD units, return flask to incubator and check absorbance every 15-30 minutes. If absorbance reading is between 0.4 and 0.5 OD units, remove from shaker and chill on ice. This is the **log-phase host bacteria stock**. After assay, freeze remaining stock by adding glycerol to host stock in a 1:4 ratio (glycerol:stock) and placing in a 5-mL freezer vial. Label and freeze at -80°C.
6. The day of the assay, prepare enough 0.7% TSA to account for 7 mL TSA per viral dilution (typically prepared 300-400 mL).
   - ***0.7% TSA for top layer of plates used to grow E. coli C3000***: Prepare TSB and add 7 g agar/L TSB before autoclaving for 45 minutes at 121°C and 15 psi. Mix and keep molten at 45°C in water bath. Dispense 7 mL molten agar into sterile 16 x 150 mm dilution tubes with screw caps (number of tubes depends on number of samples/dilutions). Keep these tubes in 45°C water bath until ready for assay.
   - ***0.7% TSA for top layer of plates used to grow E. coli F_{amp}***: Prepare TSB and add 7 g agar/L TSB before autoclaving for 45 minutes at 121°C and 15 psi. Mix and keep molten at 45°C in water bath. Once solution has equilibrated, add 10 mL of ampicillin/streptomycin per L of TSA. Dispense 7 mL molten agar into sterile 16 x 150 mm dilution tubes with

screw caps (number of tubes depends on number of samples/dilutions). Keep these tubes in 45°C water bath until ready for assay.

7. The day of the assay, spike 4 L of reagent water with 4 mL of viral stock. Mix and add 2 L to each bucket containing a Pelikan filter. Allow spiked water to drip through filters for 30 minutes to 1 hour. Collect 1 mL each of filtered and unfiltered water samples and prepare serial dilutions in Eppendorf tubes using 1X PBS so that there will be approximately 300-2000 plaques per 1 mL dilution. (Used 10^{4}-10^{11} dilutions for assay). Serial dilutions are made by adding 0.9 mL of PBS to multiple Eppendorf tubes. An aliquot (0.1 mL) of source water is added to the first PBS-containing tube, which is vortexed. A 0.1 mL volume is then taken from this tube and added to the next PBS-containing tube, which is vortexed. This is repeated over and over until the desired number of successive dilutions are made.
8. Once viral dilutions are prepared, move over to TSA in water bath. Add 0.1 mL log phase host (which has been chilling on ice) to 7 mL of 45°C 0.7% TSA. Quickly add 0.1 mL viral dilution to TSA and mix. Cap tube, invert, and immediately pour onto 1.5% TSA bottom layer plate. Quickness is needed so that agar does not solidify before being poured onto the plate. Agar will begin to set at around 37°C. Repeat for other dilutions. Once agar has solidified, cover, invert, and incubate plates for 16-24 hours at 36 ± 1°C. Make sure to do a negative control in which the 0.1 mL viral solution is replaced with 0.1 mL 1X PBS.
9. Count the total number of plaques ("circular zones of clearing") present per plate. Report results as PFU/100 mL water sample, accounting for dilutions.

5. Results and Discussion

5.1 Turbidity Removal

Tests for turbidity removal were performed on the ceramic candle filters in Kenya and at MIT. Results and discussion of these tests are detailed in Sections 5.1.1 through 5.1.4. Data from studies can be found in Appendix H.

5.1.1 Results of Turbidity Studies Performed in Kenya

In Kenya, filtered and unfiltered turbidity readings were compared to determine turbidity removal. Turbidity readings for the unfiltered water (diluted Nairobi river source) ranged from 15 to 31 NTU. All filters but the Pozzani consistently reduced turbidity to below 1 NTU. Initial turbidity measurements were made three hours after submerging the ceramic candle filter elements in polluted water. Final turbidity measurements were made 20 hours after initially adding polluted water. Results from turbidity tests are shown in Tables 5.1 and 5.2 and are depicted in Figures 5.1 and 5.2.

Table 5.1: Filtered Water Turbidity Readings Obtained in Kenya (NTU)

	Turbidity (NTU) 3 hrs		Turbidity (NTU) 20 hrs			
Filter	**Run 1**	**Run 2**	**Run 1**	**Run 2**	**Overall Average**	**Std. Dev.**
AquaMaster 1	0.27	0.66	0.31	0.45	0.42	0.18
AquaMaster 2	0.30	0.58	0.19	0.41	0.37	0.17
Doulton 1	0.14	0.49	0.33	0.28	0.31	0.15
Doulton2	0.45	0.77	0.27	0.33	0.46	0.22
Stefani 1	0.13	0.66	0.23	0.79	0.45	0.32
Stefani 2	0.13	0.10	0.13	0.15	0.13	0.02
Pelikan 1	0.15	0.55	0.31	0.51	0.38	0.18
Pelikan 2	0.15	0.43	0.10	0.23	0.23	0.15
Pozzani 1	0.18	1.03	0.21	0.36	0.44	0.40
Pozzani 2	0.32	1.42	0.30	0.45	0.62	0.53

As can be seen from Table 5.1, filtration by Stefani São João filter number 2 resulted in the lowest overall average turbidity (0.13±0.02 NTU). The low standard deviation for this filter shows a level of consistency with regard to reducing turbidity. Filtration by all other filters except for Pozzani filter number 2 resulted in overall average turbidities of between 0.31 and 0.46 NTU; these filters produced water with similar levels of turbidity. Filtration by the Pozzani filters for Run 2 after 3 hours resulted in turbidities above 1 NTU. These values do not coincide with the other turbidity readings, revealing a possible error in the data or defect in the filters. If this value is ignored, then the average overall turbidity will fall within the range of turbidities observed for the other filters.

Table 5.2: Percent Turbidity Removal by Filters in Kenya

	Percent Turbidity Removed After 3 Hours			Percent Turbidity Removed After 20 Hours			
Filter	**Run 1**	**Run 2**	**Average**	**Run 1**	**Run 2**	**Average**	**Total Avg.**
AquaMaster 1	98.2	97.9	98.0	97.9	98.5	98.2	98.1
AquaMaster 2	98.0	98.1	98.1	98.7	98.7	98.7	98.4
Doulton 1	99.1	98.4	98.8	97.8	99.1	98.4	98.6
Doulton2	97.0	97.5	97.2	98.2	98.9	98.6	97.9
Stefani 1	99.1	97.9	98.5	98.5	97.5	98.0	98.2
Stefani 2	99.2	99.4	99.3	99.2	99.2	99.2	99.3
Pelikan 1	99.1	97.1	98.1	98.2	97.3	97.7	97.9
Pelikan 2	99.1	97.7	98.4	99.4	98.8	99.1	98.7
Pozzani 1	99.0	94.5	96.7	98.8	98.1	98.4	97.6
Pozzani 2	98.1	92.4	95.2	98.3	97.6	97.9	96.6

As can be seen from Table 5.2, the filters achieved an average percent turbidity removal of 96.6-99.3%. The average percent turbidity removal for the AquaMaster filters was 98.3%. Average percent turbidity removal for the Doulton Super Sterasyl filters was also 98.3%. The Stefani São João filters possessed an average turbidity removal of 98.8%. The Pelikan filters possessed an average turbidity removal of 98.3%. The Pozzani filters performed the worst with regard to turbidity removal, though the relative difference is negligible. The average turbidity removal obtained by the Pozzani filters was 97.1%.

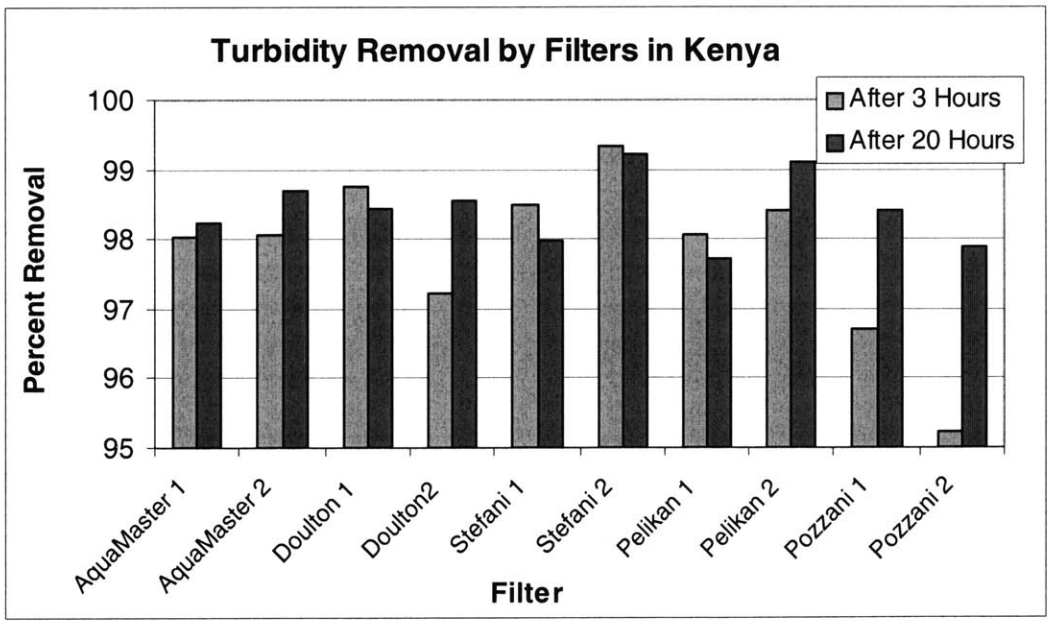


Figure 5.1: Percent Turbidity Removal by Filters in Kenya

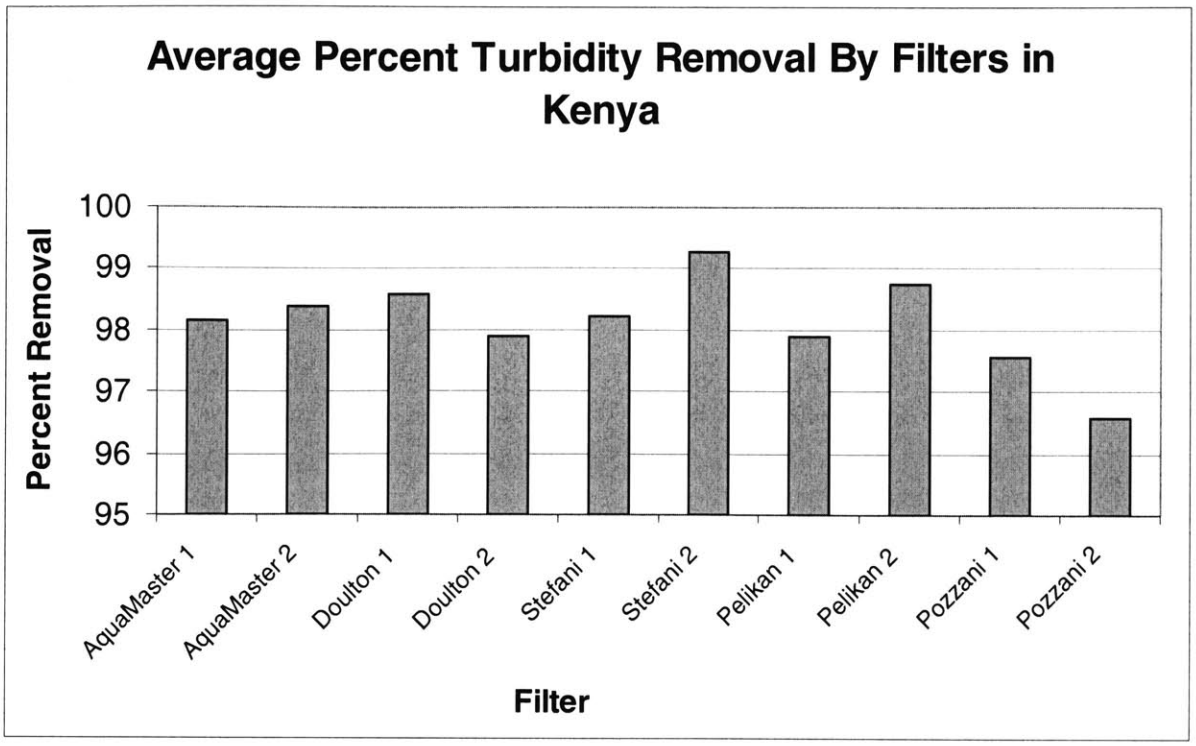


Figure 5.2: Average Percent Turbidity Removal by Filters in Kenya

Figures 5.1 and 5.2 reveal that Stefani São João filter number 2 performed the best at removing turbidity from the diluted Nairobi source water. This filter had an average percent removal of 99.3%. Pozzani filter number 2, on the other hand, performed the worst, with an average percent removal of 96.6%. However, the difference in performance is still negligible.

5.1.2 Discussion of Turbidity Results Obtained in Kenya

Despite the slight variations in turbidity removal observed for the Pozzani filters and Stefani São João filter number 2, the overall turbidity removal for each brand of filter is relatively comparable. There is no one brand of filter that performs considerably better than the others. And although the Pozzani filters appeared to perform the worst, the turbidity obtained for Run 2 after 3 hours was inconsistent with other turbidity values obtained for these filters; these high turbidities may be outliers. If they are ignored, the Pozzani filters showed average turbidities similar to the other brands.

Statistics were not performed on the Kenya data because only a few runs were performed. Many more tests need to be performed on the filters in order to generate conclusive data. For example, more tests will reveal if the data obtained for Run 2 after 3 hours for the Pozzani filters is in fact abnormal. If it is *not* abnormal, this could reveal that the Pozzani filters need time to acclimate to the polluted source. This might suggest that several volumes of water be allowed to run through these filters before consuming filtered water.

It appears that on average, all of the above filters will suffice at reducing the turbidity of a polluted source to below 1 NTU, the maximum level of turbidity allowed by the EPA for treated water.

However, only Stefani São João filter number 2 reduced the level of turbidity (0.13 ±0.02 NTU) to less than 0.3 NTU, the value below which the EPA requires 95% of daily treated water samples to fall. None of the filters achieved a level below 0.1 NTU, the maximum turbidity recommended by WHO for achieving effective disinfection. As previously stated, the results from the Kenya tests are not conclusive. Many more tests need to be performed in order to obtain a clearer understanding of the water purifying capabilities of the studied ceramic candle filters.

5.1.3 Results of Turbidity Studies Performed at MIT

With one exception, the same filters tested in Kenya were subjected to further testing at MIT. The only difference was Pelikan filter number 2, which was replaced with a new Pelikan filter due to breakage in transit from Kenya to the U.S. At MIT, filtered and unfiltered turbidity readings were compared to determine turbidity removal efficiency. Turbidity readings for the unfiltered Charles River water ranged from 1.8 NTU to 8.4 NTU. These values are significantly lower than NTU values for the polluted Nairobi source, and so percent turbidity removed by filters at MIT was not as high as percent turbidity removed in Kenya; the fact that the raw water had such a low turbidity made it difficult to discern the capacity of the filters to reduce turbidity. Results from turbidity tests performed at MIT are shown in Tables 5.3 and 5.4 and are depicted in Figure 5.3. Because over three runs were performed, turbidity results obtained at MIT were subjected to statistical analysis.

Table 5.3: Filtered Water Turbidity Readings Obtained at MIT

	Filtered Turbidity Readings Obtained at MIT (NTU)										
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Avg.**	**St. Dev.**
AquaMaster 1	0.41	0.37	0.45	0.53	0.28	0.18	0.61	0.38	0.36	0.40	0.13
AquaMaster 2	0.59	0.50	0.41	0.43	0.22	0.18	0.31	0.50	0.35	0.39	0.14
Doulton 1	0.53	0.28	0.28	0.28	0.18	0.09	0.13	0.40	0.32	0.28	0.13
Doulton 2	0.39	0.53	0.19	0.43	0.23	0.16	0.12	0.31	0.31	0.30	0.14
Stefani 1	0.16	0.27	0.27	0.42	0.15	0.15	0.27	0.26	0.45	0.27	0.11
Stefani 2	0.03	0.14	0.11	0.20	0.09	0.11	0.27	0.18	0.46	0.18	0.13
Pelikan 1	0.08	0.11	0.10	0.15	0.07	0.08	0.03	0.10	0.12	0.09	0.03
Pelikan 2	0.06	0.10	0.09	0.23	0.05	0.06	0.01	0.15	0.13	0.10	0.06
Pozzani 1	1.36	0.58	0.27	0.18	0.07	0.18	0.22	0.06	0.26	0.36	0.41
Pozzani 2	1.40	0.83	0.46	0.67	0.17	0.20	0.23	0.27	0.41	0.52	0.40

As observed in Kenya, all filters but the Pozzani consistently reduced turbidity to below 1 NTU. In fact, all filters but the Pozzani consistently showed turbidity readings below 0.6 NTU when tested at MIT. It should be noted that the high turbidity readings observed for the Pozzani filters are only seen for runs 1 and 2. After this, the turbidity of filtered water is similar to the turbidities obtained by the other filters. Filtration by the Pelikan filters resulted in the lowest turbidities (0.09±0.03 NTU for #1 and 0.10±0.06 NTU for #2). Stefani filter number 2 again showed good performance; this filter showed an average turbidity of 0.18±0.13 NTU. All other filters (including Pozzanis) showed comparable average turbidities, which ranged from 0.27-0.52 NTU.

Table 5.4: Percent Turbidity Removal by Filters at MIT

	Percent Turbidity Removal by Filters at MIT									
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Average**
AquaMaster 1	93.1	95.6	87.1	92.1	90.3	90.2	77.2	81.1	87.5	88.3
AquaMaster 2	90.2	94.0	88.3	93.6	92.4	90.1	88.5	74.8	87.9	88.8
Doulton 1	91.2	96.7	92.0	95.8	93.9	94.9	95.1	79.8	89.1	92.1
Doulton 2	93.4	93.7	94.5	93.6	91.9	91.3	95.5	84.3	89.2	91.9
Stefani 1	97.4	96.8	92.2	93.7	94.8	91.7	89.7	87.0	84.6	92.0
Stefani 2	99.6	98.4	96.8	97.0	96.9	94.0	89.8	90.8	84.3	94.2
Pelikan 1	98.7	98.7	97.2	97.7	97.6	95.7	98.9	95.0	95.8	97.3
Pelikan 2	98.9	98.9	97.3	96.6	98.4	96.7	99.5	92.7	95.5	97.2
Pozzani 1	77.2	93.1	92.1	97.3	97.5	90.2	91.7	96.8	91.1	91.9
Pozzani 2	76.7	90.2	86.6	89.9	94.2	89.0	91.2	86.3	86.0	87.8

As can be seen from Table 5.4, the filters tested at MIT achieved a turbidity removal of 88.3-97.3%. The AquaMaster filters had the lowest percent turbidity removal (88.6%) of the filters studied using Charles River water. The Doulton Super Sterasyl Filters performed better than the AquaMaster filters; they had an average percent removal of 92.0%. The Stefani São João filters had an average percent removal of 93.1%. The Pelikan filters showed the largest percent turbidity removal: 97.3%. Finally, the Pozzani filters possessed an average percent turbidity removal of 89.9%.

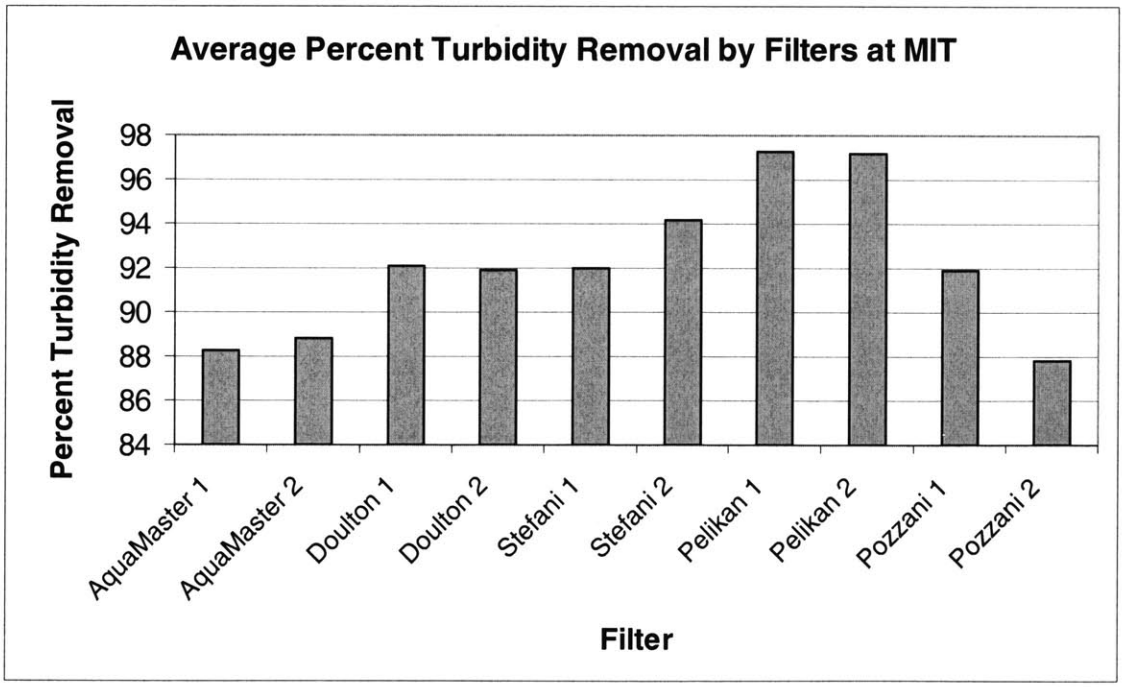


Figure 5.3: Average Percent Turbidity Removal by Filters at MIT

From Figure 5.3, it is apparent that the Pelikan filters performed the best at removing turbidity from the Charles River water. Only this brand achieved the level of *percent* turbidity removal observed for the filters in Kenya. The high percent turbidity removal observed for the Pelikan

would suggest smaller pores sizes relative to the other filter brands. When tested with Charles River water at MIT, the Pelikan reduced turbidity to below 0.1 NTU. Stefani São João filter number 2 also performed well when compared to the other filters; results at MIT are similar to the results observed in Kenya with regard to relative performance.

Table 5.5: Probability that Turbidities Obtained by Compared Filters are Significantly Different

Probability that Filters Remove Different Amounts of Turbidity Based on MIT Data										
Filter	**AQM 1**	**AQM 2**	**DL 1**	**DL 2**	**SSJ 1**	**SSJ 2**	**PL 1**	**PL 2**	**PZ 1**	**PZ 2**
AQM 1	1	0.8320	0.1649	0.1281	0.1468	0.0346	0.0016	0.0016	0.2190	0.8598
AQM 2	0.8320	1	0.2308	0.1881	0.2108	0.0511	0.0021	0.0022	0.2949	0.6832
DL 1	0.1649	0.2308	1	0.9528	0.9697	0.3881	0.0176	0.0203	0.9493	0.0932
DL 2	0.1281	0.1881	0.9528	1	0.9838	0.2561	0.0000	0.0027	0.2527	0.0048
SSJ 1	0.1468	0.2108	0.9697	0.9838	1	0.3276	0.0061	0.0073	0.9729	0.0741
SSJ 2	0.0346	0.0511	0.3881	0.2561	0.3276	1	0.1075	0.1260	0.3973	0.0145
PL 1	0.0016	0.0021	0.0176	0.0000	0.0061	0.1075	1	0.9234	0.0322	0.0003
PL 2	0.0016	0.0022	0.0203	0.0027	0.0073	0.1260	0.9234	1	0.0361	0.0045
PZ 1	0.2190	0.2949	0.9493	0.2527	0.9729	0.3973	0.0322	0.0361	1	0.1398
PZ 2	0.8598	0.6832	0.0932	0.0048	0.0741	0.0145	0.0003	0.0045	0.1398	1

The values listed in Table 5.5 were obtained by performing the statistical t-test on turbidity results obtained at MIT. The t-test is used to determine whether "two samples are likely to have come from the same two underlying populations that have the same mean (Excel, 2005)." In other words, the t-test reveals the likelihood that the turbidity removals observed were significantly similar or different for each combination of filters. Values less than 0.05 (5%) reveal a statistically significant difference in turbidities. The brand of filter that showed statistically significant differences in turbidities when compared to all but Stefani São João filter number 2 was the Pelikan (values highlighted in red). Thus the Pelikans performed significantly better (over 95% confidence) than all but Stefani São João filter number 2 at removing turbidity from the Charles River water.

5.1.2 Discussion of Turbidity Results Obtained at MIT

Despite the supposed poorer performance observed for all but the Pelikan filters at MIT, it should be noted that all filters but the Pozzani consistently reduced turbidity levels to below 0.60 NTU. In Kenya all but the Pozzani filters reduced turbidity to below 0.80 NTU. Thus, the individual filters were capable of achieving similar turbidities despite the initial difference in turbidity of the unfiltered source. From the obtained results and statistics, the Pelikan filters appear to be the best at reducing turbidity present in Charles River water. While all filters tested at MIT on average reduced turbidity to below the EPA limit of 1 NTU, only the Pelikan filters reduced turbidity to below the ideal 0.3 NTU value prescribed by the EPA. This ability of the Pelikan to reduce turbidity is likely due to small pore sizes within the candle, the majority of which range in size from 0.1 to 1 μm (Bershteyn et al.). However, even the Pelikan failed to reduce turbidity to below the WHO recommended turbidity of 0.1 NTU.

Similar to the results obtained in Kenya, the Pozzani filters performed poorly at removing turbidity during the initial runs. As seen in Tables 5.3 and 5.4, the Pozzani performed poorly during Runs 1

and 2. The average value of filtered water in Run 1 was 1.38 NTU. The average percent removal for Run 1 by the Pozzani filters was a low 77.0%. After the initial run, however, the Pozzani filters performed better. The data for the initial runs may be outliers, or it may be that the Pozzani filters needed time to become acclimated to the polluted water source. For example, it may be possible that a slight buildup of raw water source particles on the filter surface is necessary to achieve better turbidity removal by these filters. As mentioned in the Kenya discussion, this may suggest that several volumes of water should be allowed to run through the Pozzani before consuming filtered water.

5.2 Flow Rate

Flow Rate tests were performed on the studied filters in Kenya and at MIT. Results obtained from these tests are detailed in Sections 5.2.1 through 5.2.4. Data from studies can be found in Appendix H.

5.2.1 Results of Flow Rate Studies Performed in Kenya

In Kenya, initial and final flow rate tests were performed for two runs of filter testing. Initial flow rate determinations were made three hours after submerging the filters in polluted water. Final flow rate measurements were made 20 hours after initially adding polluted water. Flow rates for individual candle filters ranged from 0.035 L/hr to 0.454 L/hr. Results from flow rate tests are shown in Table 5.6 and are depicted in Figures 5.4 and 5.5. It should be noted that only two runs of flow rate measurements were made in Kenya. Long-term examination of flow rate performance was outside the scope of this study.

Table 5.6: Flow Rate Readings Obtained for Filters While in Kenya

	Flow Rate (L/hr) After 3 Hours			Flow Rate (L/hr) After 20 Hours				
Filter	**Run 1**	**Run 2**	**Average**	**Run 1**	**Run 2**	**Average**	**Total Avg.**	**St. Dev.**
AquaMaster 1	0.138	0.143	0.141	0.037	0.042	0.040	0.090	0.058
AquaMaster 2	0.130	0.161	0.146	0.039	0.048	0.044	0.095	0.060
Doulton 1	0.423	0.340	0.382	0.096	0.104	0.100	0.241	0.166
Doulton 2	0.357	0.350	0.354	0.110	0.100	0.105	0.229	0.144
Stefani 1	0.160	0.130	0.145	0.045	0.042	0.044	0.094	0.060
Stefani 2	0.124	0.216	0.170	0.040	0.053	0.047	0.108	0.081
Pelikan 1	0.158	0.454	0.306	0.060	0.057	0.059	0.182	0.187
Pelikan 2	0.169	0.374	0.272	0.090	0.095	0.093	0.182	0.133
Pozzani 1	0.100	0.188	0.144	0.035	0.042	0.039	0.091	0.071
Pozzani 2	0.085	0.260	0.173	0.046	0.051	0.049	0.111	0.101

As can be seen from Table 5.6, flow rates measured after three hours (initial) were much greater than flow rates measured after 20 hours (final). The average initial flow rate for the AquaMaster filters was 0.144 L/hr; the final value was 0.042 L/hr. The final value is less than a third of the initial flow rate. The average over initial and final flow rates for the AquaMaster filters was 0.093±0.059 L/hr. The Doulton Super Sterasyl filters performed better than the AquaMaster filters. For the Doulton, the average initial flow rate was 0.368 L/hr; the final was 0.103 L/hr. The overall average flow rate was 0.235±0.155 L/hr. The Stefani São João's performance was similar

to the AquaMaster's performance with regard to flow rate. Average initial, final, and overall flow rate values were 0.158 L/hr, 0.46 L/hr, and 0.101±0.070 L/hr, respectively. Like the Doulton, the Pelikan filters also possessed relatively higher flow rates. The average initial, final, and overall flow rate values for the Pelikan were 0.289 L/hr, 0.076 L/hr, and 0.182±0.16 L/hr, respectively. The Pozzani filter performed similar to the AquaMaster and Stefani filters. Values of initial, final, and overall flow rate for this brand were 0.159 L/hr, 0.044 L/hr, and 0.101±0.086 L/hr, respectively.

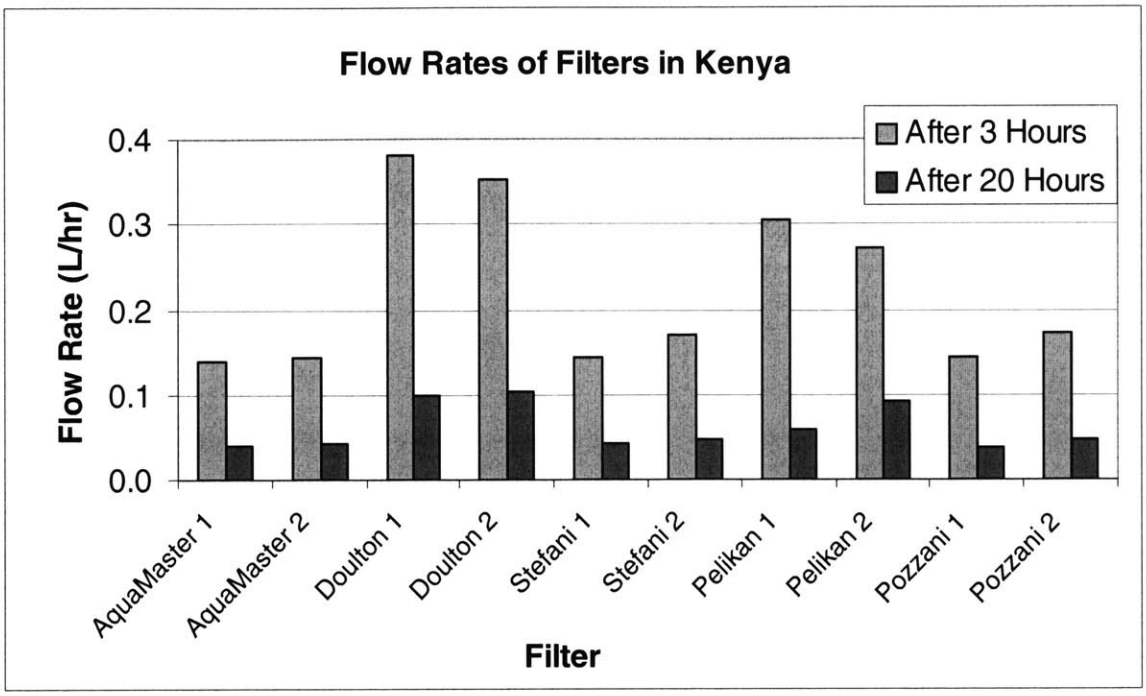


Figure 5.4: Initial and Final Flow Rate Determinations for Filters in Kenya

5.2.2 Discussion of Flow Rate Results Obtained in Kenya

Figure 5.4 illustrates the results of Table 5.6. From this graph it is apparent that the flow rates decrease significantly 20 hours after first submerging the filters in water. This decline in flow rate over time can be explained by two factors. First of all, the water used to test these filters was quite turbid (15 – 31 NTU). There were suspended leaves, grass, and feces visible in the water source obtained in Nairobi. Thus, as time passed, material may have built up on the exterior surface of the filter element, clogging the pores and concomitantly decreasing flow rate. The second possible explanation could be due to the fact that as water flowed out of the filter, less water remained to be filtered. Most buckets possessing filters were half empty after sitting for 20 hours. Thus there was less surface area of the filter being contacted by water as the water level receded. Also, the volume of water (and hydraulic head) was greatest when water was first added to the filter. Over time there was a lower volume of water and so there was less water pressure on the filter to push water through. This relationship between flow rate and water pressure can be explained in more detail by Darcy's Law (see Appendix A).

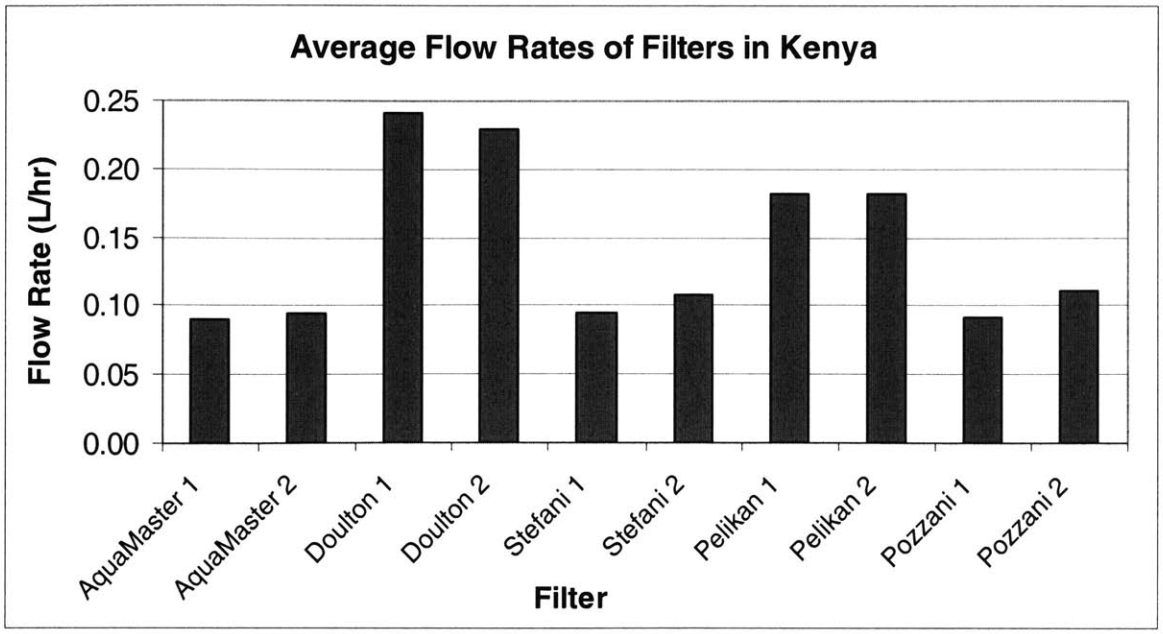


Figure 5.5: Average Flow Rates of Filters Tested in Kenya

From Figure 5.5, it is apparent that the Doulton Super Sterasyl possessed the highest flow rate among the studied filters. The Pelikan possessed the second highest flow rate, while the remaining brands all had lower comparable flow rates. It should be noted that the flow rates observed in this study are proportional to candle length and volume (hydraulic head). The Doulton Super Sterasyl was the longest filter tested, with a length of 25.4 cm and a diameter of 5.1 cm. The Doulton possessed the most surface area out of the tested filters; a greater surface area means more pore space for water to pass through.

The long length of the Doulton Super Sterasyl also meant that more water was added initially to the bucket. For each filter tested, polluted water was added until the water level was just above the top of the ceramic candle filter element. Since the Doulton was the longest filter, it was subjected to the greatest volume of water (13.5 L). Thus it experienced the greatest water pressure. The Pelikan possessed the second highest flow rate; it was also the second longest filter, with a length of 19.7 cm and a diameter of 5.4 cm. It was also subjected to the second greatest volume of water (7.5 L). The remaining filters (AquaMaster, Stefani, Pozzani) had similar flow rates, lengths, and volumes; each was about 10 cm long and was subjected to a volume of 3.5 L.

Results of this study reveal that filters possessing the greatest surface area and water pressure produced the fastest flow rates. Flow rate is also dependent on permeability (porosity) of the ceramic candle. However, the effect of this parameter on flow rate was hard to discern with surface area and water pressure in the picture. Results of turbidity and microbial removal studies are more indicative of pore/channel size.

Despite the high flow rate observed for the Doulton Super Sterasyl relative to the other filters, the average flow rate of 0.235 L/hr observed using polluted Nairobi water is insufficient to support the daily requirement of water for an individual. According to WHO, the minimum necessary volume of water required per person per day is 7.5 L (Howard, 2004). At the flow rate observed, a single

Doulton Super Sterasyl candle filter element could only provide 4.8 L of filtered Nairobi water in one day. This amount is not even enough to support one person, let alone a whole family. This reveals that the other filters, with their slower flow rates, are also extremely inadequate when it comes to filtering a sufficient volume of Nairobi river water.

5.2.3 Results of Flow Rate Studies Performed at MIT

At MIT, flow rate tests were performed for nine runs of filter testing using Charles River water. Flow rate determinations were made approximately three hours after submerging the filters in Charles River water. Flow rates for the studied filters ranged from 0.021 L/hr to 0.929 L/hr. Results from flow rate tests are shown in Table 5.7 and are depicted in Figure 5.6. Because over three runs were performed, the flow rate data obtained at MIT was also subjected to statistical analysis.

Table 5.7: Flow Rate Readings Obtained for Filters at MIT

	Flow Rate Readings Obtained at MIT (L/hr)										
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Avg.**	**Std. Dev.**
AquaMaster 1	0.256	0.17	0.038	0.145	0.16	0.097	0.021	0.165	0.218	0.141	0.077
AquaMaster 2	0.332	0.249	0.123	0.194	0.189	0.127	0.047	0.137	0.214	0.179	0.083
Doulton 1	0.759	0.395	0.263	0.357	0.479	0.221	0.2	0.767	0.844	0.476	0.252
Doulton 2	0.929	0.725	0.376	0.617	0.552	0.498	0.2	0.928	0.723	0.616	0.242
Stefani 1	0.434	0.41	0.212	0.188	0.241	0.187	0.134	0.339	0.226	0.263	0.106
Stefani 2	0.443	0.282	0.157	0.195	0.202	0.145	0.112	0.226	0.212	0.219	0.097
Pelikan 1	0.346	0.3	0.201	0.27	0.318	0.229	0.145	0.263	0.273	0.261	0.062
Pelikan 2	0.16	0.155	0.096	0.145	0.145	0.148	0.112	0.15	0.182	0.144	0.026
Pozzani 1	0.15	0.282	0.079	0.222	0.277	0.23	0.078	0.201	0.182	0.189	0.075
Pozzani 2	0.088	0.297	0.087	0.117	0.242	0.226	0.071	0.262	0.15	0.171	0.086

Of the filters tested at MIT using Charles River water, the AquaMaster filters possessed the slowest flow rate. The average flow rate obtained for the AquaMaster filters using Charles River water was 0.160±0.08 L/hr. Similar to Kenya, the Doulton Super Sterasyl possessed the greatest flow rate out of the filters tested using Charles River water. Average flow rate for the Doulton Super Sterasyl was 0.546±0.247 L/hr. Flow rate for the Stefani São João was less than that of the Doulton but greater than that of the AquaMaster. Flow rate for the Stefani São João was found to be 0.241±0.102 L/hr. The Pelikan performed similar to the Stefani Stefani São João. Average flow rate for this brand was 0.203±0.044 L/hr. The Pelikan filters were the only filters whose average flow rate obtained using Charles River water was comparable to the average flow rate obtained using polluted Nairobi water. Finally, the Pozzani filters possessed an average flow rate of 0.180±0.080 L/hr.

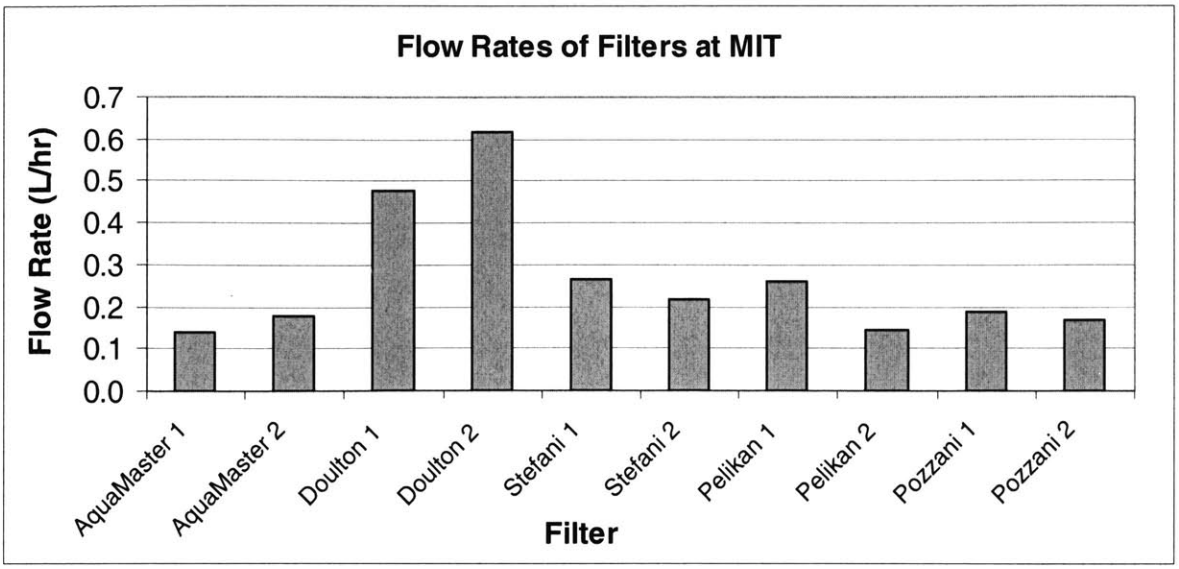


Figure 5.6: Average Flow Rates of Filters Tested at MIT

Table 5.8: Probability that Flow Rates Obtained by Compared Filters are Significantly Different

Probability that Filters Possess Different Flow Rates Based on MIT Data										
Filter	**AQM 1**	**AQM 2**	**DL 1**	**DL 2**	**SSJ 1**	**SSJ 2**	**PL 1**	**PL 2**	**PZ 1**	**PZ 2**
AQM 1	1	0.3295	0.0037	0.0003	0.0136	0.0784	0.0024	0.9269	0.2018	0.4488
AQM 2	0.3295	1	0.0075	0.0005	0.0787	0.3597	0.032	0.2494	0.7943	0.8435
DL 1	0.0037	0.0075	1	0.2453	0.04	0.0166	0.0343	0.0041	0.009	0.0065
DL 2	0.0003	0.0005	0.2453	1	0.0015	0.0007	0.0018	0.0003	0.0006	0.0005
SSJ 1	0.0136	0.0787	0.04	0.0015	1	0.3705	0.9445	0.0092	0.1062	0.0598
SSJ 2	0.0784	0.3597	0.0166	0.0007	0.3705	1	0.3019	0.0503	0.471	0.2828
PL 1	0.0024	0.032	0.0343	0.0018	0.9445	0.3019	1	8E-05	0.0428	0.0235
PL 2	0.9269	0.2494	0.0041	0.0003	0.0092	0.0503	8E-05	1	0.1183	0.8837
PZ 1	0.2018	0.7943	0.009	0.0006	0.1062	0.471	0.0428	0.1183	1	0.6455
PZ 2	0.4488	0.8435	0.0065	0.0005	0.0598	0.2828	0.0235	0.8837	0.6455	1

The values listed in Table 5.8 were obtained by performing the statistical t-test on flow rate results obtained at MIT. Values less than 0.05 (5%) reveal a statistically significant difference in flow rates between filters. The brand of filter that showed statistically significant differences in flow rates when compared to other brands was the Doulton Super Sterasyl (values highlighted in red). These filters achieved flow rates that were significantly higher than the flow rates obtained by other brands subjected to treatment with Charles River water. The high relative flow rates observed for the Doulton are likely due to the large surface area of the candle (because of its long length) and the large volume of water (fluid pressure) used for testing.

5.2.4 Discussion of Flow Rate Results Obtained at MIT

From Table 5.7, it is apparent that the average flow rates determined using Charles River water were greater in all cases than the average flow rates determined using Nairobi river water. However, it should be noted that the average flow rates obtained after three hours of exposure to Nairobi river water are similar to the overall flow rates obtained using Charles River water. This makes sense since flow rate tests at MIT were also performed approximately three hours after initially adding raw water to the filters. For all filters but the Pelikans, the average flow rate values determined after three hours using Nairobi water were less than the average flow rates obtained using Charles River water. The level of pollution present in the Nairobi water would explain why the initial flow rates are lower (for all but the Pelikan filters) than the flow rates determined using Charles River water; the Nairobi water contains more suspended solids and bacteria, and is more turbid. A possible explanation for the slow flow rate of Pelikan filter number 2 at MIT may be due to the fact that the filter tested at MIT was new; all of the other filters were tested in Nairobi and cleaned at least once prior to testing at MIT. Thus, the other filters had already had time to become "broken in," or acclimated. This does not explain the contradiction observed for Pelikan filter number 1, however.

It should be noted that the flow rates obtained for Run 3 are somewhat lower than the values obtained for other runs. This may be because this flow rate test was started later than other flow rate tests. When this flow rate test began, the water level was already at about two-thirds the height of the filters. In other words, approximately one-third of the filter was exposed to air and was not in contact with water. The facts that there was a lower volume of water present then usual, and that a significant portion of the filter element was exposed to air, may explain the low flow rates observed for this run. Also important to note are the flow rates obtained during Run 7, which were also somewhat slow when compared to other runs. Suspecting that the filters were beginning to clog, each candle was gently scrubbed using tepid water and steel wool after this run. The flow rates for run 8 were back to normal, revealing that particulate buildup was likely responsible for the slow flow rates observed for Run 7.

Similar to Kenya, studies performed on filters at MIT revealed the Doulton Super Sterasyl to possess the greatest flow rate. This brand showed significantly higher flow rates than all other brands tested. Reasons for this are the same as those explained in Section 5.2.2. The flow rates of the other filters were comparable. Unlike results obtained in Kenya, the Pelikan did not perform as well relative to other filters tested at MIT. The Stefani Stefani São João filters actually possessed a higher average flow rate than the Pelikan filters at MIT. However, Pelikan filter number 1 did perform significantly better than the AquaMaster and Pozzani filters with regard to flow rate. Thus the behavior of Pelikan filter number 2 may not be normal. More tests need to be performed on other Pelikan filters before conclusions can be drawn.

It should be noted that values obtained for flow rate at MIT for the Pelikan were relatively close to flow rate values obtained in Kenya. This reveals the Pelikan to possess a consistent flow rate, regardless of the level of pollution and turbidity initially present in the unfiltered water. As mentioned earlier, Pelikan filter number 2 was likely slower than Pelikan filter number 1 because it was new and had not been scrubbed/cleaned yet.

The average flow rate obtained for the Doulton Super Sterasyl using Charles River water was 0.546 L/hr. This amounts to approximately 13.1 L of filtered water per day, assuming that the flow rate does not decline (i.e. that the water level remains constant above the top of the filter element and that the filter doesn't clog). This volume is just sufficient to support two individuals' minimum requirements for drinking water. This reveals that the Doulton Super Sterasyl is adequate when it comes to filtering a sufficient volume of Charles River Water for two individuals. However, one filter alone is inadequate when it comes to filtering the volume of water required by a household (greater than two people).

5.3 Coliform Removal

Tests for removal of total coliforms and *E. coli* were performed for the studied filters in Kenya and at MIT. Results obtained from these tests are detailed in Sections 5.3.1 through 5.3.4. Data from studies can be found in Appendix H.

5.3.1 Results of Coliform Studies Performed in Kenya

In Kenya, tests for total coliforms and *E. coli* were performed for two runs of filter testing. The numbers of coliforms present in unfiltered Nairobi river water and filtered water samples were compared to determine coliform removal efficiencies. The concentration of coliforms in the diluted Nairobi source ranged from 78,000 CFU/100 mL to 1,600,000 CFU/100 mL. The concentration of *E. coli* ranged from 24,000 CFU/100 mL to 1,200,000 CFU/100 mL. The high initial concentrations of coliforms present in the diluted Nairobi water made it possible to determine log removal efficiency of the filters. Although the log scale more clearly reveals differences in coliform removal, results are also expressed as percent removal. Results from coliform removal tests are shown in Tables 5.9 and 5.10, and are depicted in Figures 5.7 and 5.8.

Table 5.9: Percent of Total Coliforms (TC) and *E. coli* (EC) Removed by Filters in Kenya

	Percent Coliforms Removed by Filters in Kenya					
Filter	**TC Run 1**	**TC Run 2**	**Avg. TC**	**EC Run 1**	**EC Run 2**	**Avg. EC**
AquaMaster 1	99.997	99.672	99.835	99.999	99.990	99.995
AquaMaster 2	99.998	99.672	99.835	<100.000	99.990	99.995
Doulton 1	99.981	99.672	99.827	99.994	99.990	99.992
Doulton 2	99.997	99.672	99.834	99.998	99.990	99.994
Stefani 1	99.975	98.828	99.402	99.974	99.917	99.946
Stefani 2	99.999	99.972	99.986	<100.000	99.977	99.988
Pelikan 1	<100.000	99.980	99.990	<100.000	99.981	99.990
Pelikan 2	99.617	99.997	99.807	99.964	99.996	99.980
Pozzani 1	99.641	99.974	99.808	99.821	99.983	99.902
Pozzani 2	99.197	99.796	99.497	99.281	99.989	99.635

All of the filters studied removed at least 99% of coliforms from the diluted Nairobi source. The AquaMaster filters performed the best overall with regard to removal of total coliforms and *E. coli* from Nairobi water. Average percent removal of total coliforms by the AquaMaster filters was 99.835%. Percent removal of *E. coli* was 99.995%. The Doulton Super Sterasyl filters also performed well at removing coliforms. These filters had average percent removals of total

coliforms and *E. coli* of 99.672% and 99.993%, respectively. The performance observed for the Stefani São João filters was not as consistent as the performance observed for other brands of filters. Stefani filter number 2 performed better than filter number 1. The average percent removal of total coliforms for these filters was 99.694%. The average removal of *E. coli* was 99.967%. The Pelikan filters also performed well with regard to removing coliforms. The average percent removals of total coliforms and *E. coli* for these filters were 99.899% and 99.985%, respectively. Again, as with flow rate data, the Pozzani filters performed the worst out of the filters studied. The average percent removal of total coliforms was 99.653%, and the average percent removal of *E. coli* was 99.769%.

Table 5.10: Log Removal of Total Coliform and E. coli by Filters in Kenya

Log Removal of Total Coliforms (TC) and *E. coli* by Filters in Kenya				
Filter	**TC Run 1**	**TC Run 2**	***E. coli* Run 1**	***E. coli* Run 2**
AquaMaster 1	4.543	2.484	5.183	4.004
AquaMaster 2	4.816	2.484	5.308	4.004
Doulton 1	3.730	2.484	4.217	4.004
Doulton 2	4.473	2.484	4.655	4.004
Stefani 1	3.604	1.931	3.585	3.083
Stefani 2	5.226	3.547	>5	3.631
Pelikan 1	>5	3.699	>5	3.718
Pelikan 2	2.417	4.588	3.442	4.371
Pozzani 1	2.445	3.588	2.748	3.769
Pozzani 2	2.096	2.691	2.143	3.973

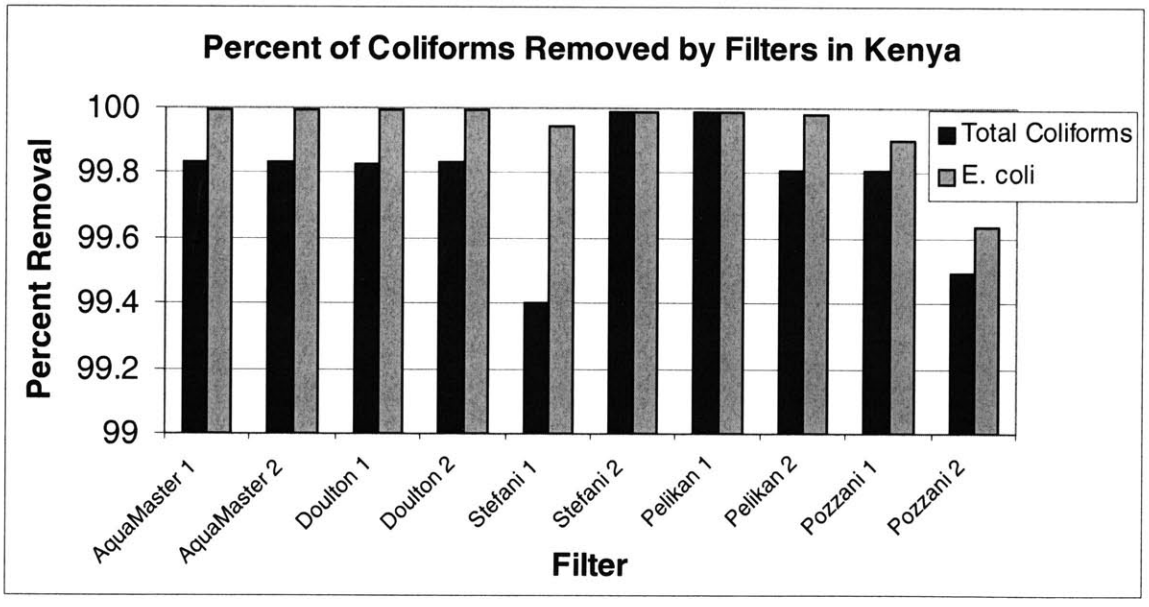


Figure 5.7: Percent of Coliforms Removed by Filters in Kenya

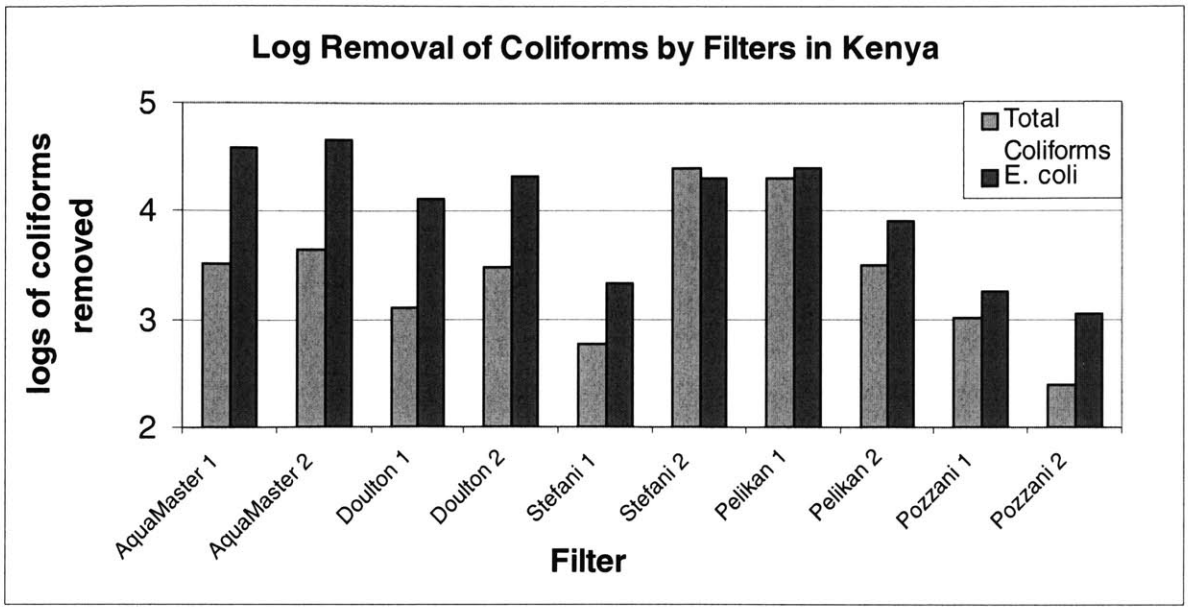


Figure 5.8: Graph of Average Log Removal of Coliforms by Filters in Kenya

5.3.2 Discussion of Coliform Results Obtained in Kenya

From the above graph, it is apparent that the AquaMaster filters were most effective at removing *E. coli* from the polluted Nairobi source. The AquaMaster filters possess both carbon and silver nitrate. The high *E. coli* removal relative to the other brands may be due in part to the bactericidal properties of the silver or to smaller pore sizes of the AquaMaster filters. The silver can not be held responsible for the observed removal, however, as the Pozzani filters also have silver nitrate but showed very poor removal of *E. coli.* That being said, the concentrations of silver nitrate present in the AquaMaster and Pozzani filters are unknown.

Stefani São João filter number 2 and Pelikan filter number 1 were the most effective at removing total coliforms. The poor performance of Stefani filter number 1 relative to its counterpart may be due to minute hairline cracks which only became visible upon returning to MIT. It should be noted that neither the Stefani São João filters nor the Pelikans possess silver on the interior of the candle element. Their high total coliform removal efficiencies are probably a result of small pore sizes; the majority of pores in the Pelikan range in size from 0.1 to 1 μm (Bershteyn et al.).

From the above data it is hard to select one brand of filter that performs significantly better than the others; especially since not enough runs were performed to do a statistical analysis. The only thing that is apparent from this data is the fact that the Pozzani filters performed worse than the other brands. More tests need to be performed on more than two filters per brand for a longer duration of time if sound conclusions are to be made with regard to the water quality obtained through the use of these filters. Additionally, it should be noted that the tap water used to dilute source water contained chlorine (see Appendix C). Chlorine is a known disinfectant, and so it is possible that some of the reduction in bacterial concentrations may be due to this confounding variable.

According to the EPA, the maximum contaminant level goal (MCLG) for total coliforms in a drinking water sample is 0 CFU/L. However, the enforceable standard requires that no more than 5% of total water sampled monthly test positive for total coliforms. Under these criteria, the studied ceramic candle filters failed as water purifiers. WHO recommends that no indicator organisms be present in water intended for consumption; thus the filtered water did not meet this guideline either. All of the filtered samples tested positive for total coliforms and/or *E. coli*, even though they were capable of removing up to 4 logs of coliforms. It should not be forgotten, however, that the source water contained hundreds of thousands of coliforms per 100 mL. Thus, the filters did reduce the bacterial concentration immensely. If less polluted water was used, then the results may have met the EPA standards and WHO guidelines. Either way, it appears that these filters may act as only one component of the water treatment process. For example, chlorine disinfection or solar disinfection could be used post-filtration to eliminate any remaining bacteria.

5.3.3 Results of Coliform Studies Performed at MIT

At MIT, tests for total coliforms and *E. coli* were performed for nine runs of filter testing. The numbers of coliforms present in filtered water samples were compared to the number of coliforms present in the unfiltered Charles River water to determine coliform removal efficiencies of the studied filters. The concentration of coliforms in the Charles River water source ranged from 1400 CFU/100 mL to 6100 CFU/100 mL. The concentration of *E. coli* ranged from 140 CFU/100 mL to 550 CFU/100 mL. The low initial concentrations of coliforms present in the Charles River water made it difficult to determine log removal by the filters. Nonetheless, results are reported as both percent of coliforms removed and log removal of coliforms. Results from coliform removal tests are shown in Tables 5.11 through 5.14, and are depicted in Figures 5.9 and 5.10. Because over three runs were performed, the coliform removal data obtained at MIT was also subjected to statistical analysis.

Table 5.11: Log Removal of Total Coliforms by Filters at MIT

		Log Removal of Total Coliforms by Filters at MIT						
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**
AquaMaster 1	2.8	2.2	2.6	2.5	2.6	2.7	2.3	2.9
AquaMaster 2	>3	2.3	2.7	2.4	2.6	2.5	2.4	2.7
Doulton 1	1.9	2.1	2.5	2.1	1.9	2.4	3.3	1.8
Doulton 2	1.7	2.0	2.3	2.3	2.7	2.0	2.6	2.6
Stefani 1	1.7	1.1	1.4	1.4	2.0	1.4	1.7	1.5
Stefani 2	2.1	2.2	2.5	2.0	2.3	1.8	1.4	1.9
Pelikan 1	2.3	1.7	2.0	3.1	2.5	1.9	3.1	3.1
Pelikan 2	>3	2.1	2.5	4.1	>3	>3	>3	3.3
Pozzani 1	1.2	1.2	1.6	1.3	1.5	0.7	1.7	1.5
Pozzani 2	1.2	1.1	1.5	1.2	1.4	0.2	1.3	1.5

Table 5.12: Percent of Total Coliforms Removed by Filters at MIT

	Percent Total Coliform Removed at MIT								
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Average**
AquaMaster 1	99.9	99.4	97.4	99.7	99.8	99.8	99.5	99.9	99.4
AquaMaster 2	<100.0	99.5	99.2	99.6	99.7	99.7	99.6	99.8	99.7
Doulton 1	98.8	99.3	97.8	99.1	98.8	99.6	99.9	98.2	98.9
Doulton 2	97.9	99.0	97.5	99.4	99.8	99.0	99.8	99.7	99.0
Stefani 1	98.0	91.6	96.4	95.9	98.9	96.2	97.8	96.5	96.4
Stefani 2	99.3	99.3	98.4	99.1	99.5	98.3	95.7	98.8	98.5
Pelikan 1	99.5	97.8	98.8	99.9	99.7	98.6	99.9	99.9	99.3
Pelikan 2	<100.0	99.2	<100.0	<100.0	<100.0	<100.0	<100.0	99.9	99.9
Pozzani 1	94.1	94.4	98.5	95.4	96.8	79.49*	98.0	96.7	96.3
Pozzani 2	93.4	92.5	96.8	93.9	96.1	29.49*	94.6	96.8	94.9

The average percent of total coliforms removed by filters from Charles River water ranged from 94.9% to 99.9%. The AquaMaster, Doulton Super Sterasyl, and Pelikan filters removed more coliforms than the Stefani São João and Pozzani filters. The AquaMaster filters had an average percent removal of 99.6% and an average standard deviation of 0.5%. The Doulton Super Sterasyl filters had an average percent removal of 99.0% and a standard deviation of 0.8%. The Stefani São João possessed values of 97.5% and 1.7% for percent removal and standard deviation, respectively. On average, the Pelikan filters performed similar to the AquaMaster. The average percent removal for the Pelikans was 99.6% and the standard deviation was 0.5%. The Pozzani filters performed the worst. Their average percent removal was 95.6% and the average standard deviation was 1.7%. Percent removals from Run 6 for the Pozzani filters were not included in the average because they were so different from the values obtained during other runs. There appears to have been contamination of these samples, possibly during collection.

Table 5.13: Log Removal of *E. coli* by Filters at MIT

	Log Removal of *E. coli* by Filters at MIT								
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**
AquaMaster 1	>3	>3	2.2	>3	>3	>3	>3	>3	>3
AquaMaster 2	>3	>3	>3	>3	>3	>3	3.0	>3	>3
Doulton 1	2.3	>3	2.5	2.3	3.3	2.1	2.7	>3	1.9
Doulton 2	>3	>3	2.0	2.8	>3	2.1	2.1	>3	3.0
Stefani 1	1.8	1.7	1.9	1.1	1.9	1.1	1.6	1.8	1.2
Stefani 2	1.8	>3	2.5	2.1	3.3	>3	2.2	1.1	1.8
Pelikan 1	2.3	>3	>3	3.3	>3	>3	2.7	3.0	2.6
Pelikan 2	>3	2.6	>3	>3	>3	>3	>3	>3	3.0
Pozzani 1	0.9	1.4	>3	1.1	1.7	0.8	1.4	2.0	2.0
Pozzani 2	0.7	1.3	1.5	1.0	2.0	0.7	0.8	1.7	1.1

Table 5.14: Percent of *E. coli* Removed by Filters at MIT

	Percent of E. coli Removed by Filters at MIT								
Filter	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 6**	**Run 7**	**Run 8**	**Run 9**	**Average**
AquaMaster 1	<100.0	<100.0	99.3	<100.0	<100.0	<100.0	<100.0	<100.0	<100.0	99.9
AquaMaster 2	<100.0	<100.0	<100.0	<100.0	<100.0	<100.0	99.9	<100.0	<100.0	<100.0
Doulton 1	99.5	<100.0	99.7	99.5	99.9	99.3	99.8	<100.0	98.8	99.6
Doulton 2	<100.0	<100.0	99.0	99.9	<100.0	99.3	99.1	<100.0	99.9	99.7
Stefani 1	98.6	98.0	98.7	92.4	98.7	92.5	97.5	98.5	93.0	96.4
Stefani 2	98.6	<100.0	99.7	99.3	99.9	<100.0	99.3	92.8	98.5	98.7
Pelikan 1	99.5	<100.0	<100.0	<100.0	<100.0	<100.0	99.8	99.9	99.7	99.9
Pelikan 2	<100.0	99.8	<100.0	<100.0	<100.0	<100.0	<100.0	<100.0	99.9	<100.0
Pozzani 1	87.6	96.0	<100.0	92.9	97.8	85.7	95.7	99.0	99.1	94.9
Pozzani 2	80.0	95.5	96.7	91.0	98.9	82.1	84.8	98.0	91.8	91.0

The average percent removal of *E. coli* from Charles River water ranged from 91% to 99.95%. The AquaMaster filters possessed the greatest average percent removal of *E. coli* (99.95%); the average standard deviation was 0.1%. The Doulton Super Sterasyl filters possessed an average percent removal of 99.7% and an average standard deviation of 0.4%. The Stefani São João filters showed poorer performance; their average percent removal and standard deviation were 97.6% and 2.6%, respectively. The Pelikan filters performed second best after the AquaMaster filters. The average percent removal and standard deviation for the Pelikan filters were 99.9% and 0.2%, respectively. The Pozzani filters performed the worst. Their average percent removal was 93.0%; their standard deviation was 6.2%. This value was high compared to the other filters, revealing a level of inconsistency observed for *E. coli* removal by the Pozzani filters.

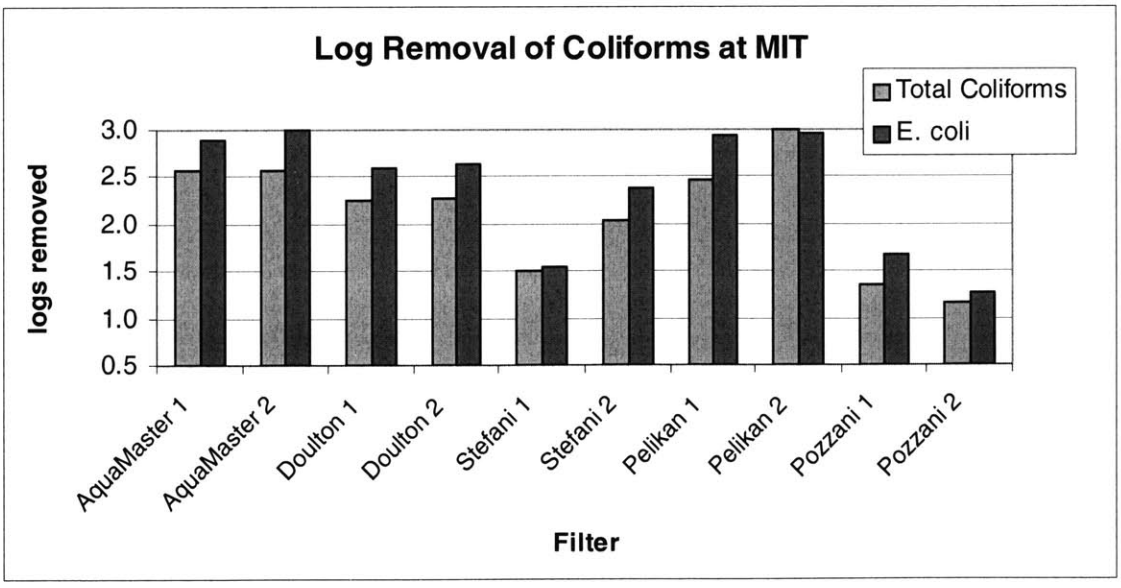


Figure 5.9: Average Log Removal of Coliforms by Filters at MIT

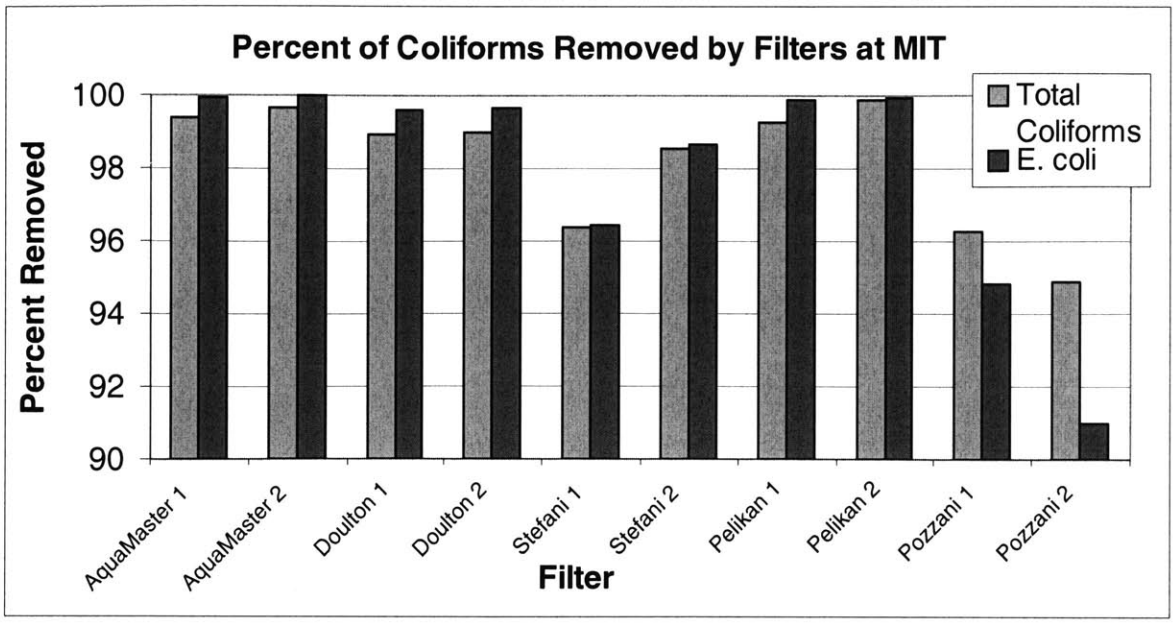


Figure 5.10: Percent of Coliforms Removed by Filters at MIT

Table 5.15: Probability that Total Coliform Removal Efficiencies Obtained by Compared Filters are Significantly Different

Probability that Filters Remove Different Amounts of Total Coliforms Based on MIT Data										
Filter	**AQM 1**	**AQM 2**	**DL 1**	**DL 2**	**SSJ 1**	**SSJ 2**	**PL 1**	**PL 2**	**PZ 1**	**PZ 2**
AQM 1	1	0.4378	0.2547	0.3735	0.0057	0.1291	0.7454	0.1556	0.002	0.0002
AQM 2	0.4378	1	0.0271	0.08	0.0041	0.0403	0.223	0.0772	0.0019	0.0003
DL 1	0.2547	0.0271	1	0.8623	0.0135	0.4461	0.3945	0.0067	0.0053	0.0004
DL 2	0.3735	0.08	0.8623	1	0.012	0.3968	0.5419	0.025	0.0045	0.0003
SSJ 1	0.0057	0.0041	0.0135	0.012	1	0.0307	0.0073	0.0028	0.917	0.1602
SSJ 2	0.1291	0.0403	0.4461	0.3968	0.0307	1	0.1862	0.0027	0.0031	0.0007
PL 1	0.7454	0.223	0.3945	0.5419	0.0073	0.1862	1	0.0392	0.0028	0.0003
PL 2	0.1556	0.0772	0.0067	0.025	0.0028	0.0027	0.0392	1	0.0013	0.0002
PZ 1	0.002	0.0019	0.0053	0.0045	0.917	0.0031	0.0028	0.0013	1	0.1513
PZ 2	0.0002	0.0003	0.0004	0.0003	0.1602	0.0007	0.0003	0.0002	0.1513	1

The values listed in Table 5.15 were obtained by performing the statistical t-test on total coliform removal results obtained at MIT. Values less than 0.05 (5%) reveal a statistically significant difference in flow rates between filters. The brand of filter that showed statistically significant differences in total coliform removal efficiencies when compared to other brands was the Pozzani (values highlighted in red). Unlike the other statistical results observed in this study, in which one brand of filter performed significantly better than the others, in the case of total coliform removal, the Pozzani filters performed significantly *worse* than all but Stefani São João filter number 1, which also performed poorly. The differences in coliform removal observed for the other brands were not significant. Statistics reveal that the differences in performance obtained by the AquaMaster, Doulton Super Sterasyl, and Pelikan filters are insignificant; total coliform removal by these brands is comparable. As stated in Section 5.3.2, the coliform removal efficiencies observed for the studied filters are related to the size of the pores.

Table 5.16: Probability that E. coli Removal Efficiencies Obtained by Compared Filters are Significantly Different

Probability that Filters Remove Different Amounts of *E. coli* Based on MIT Data										
Filter	**AQM 1**	**AQM 2**	**DL 1**	**DL 2**	**SSJ 1**	**SSJ 2**	**PL 1**	**PL 2**	**PZ 1**	**PZ 2**
AQM 1	1	0.4209	0.055	0.1571	0.0065	0.1388	0.5996	0.6576	0.0183	0.0053
AQM 2	0.4209	1	0.0195	0.0642	0.006	0.1219	0.0823	0.4205	0.0173	0.0051
DL 1	0.055	0.0195	1	0.6952	0.0105	0.2569	0.0867	0.027	0.0243	0.0064
DL 2	0.1571	0.0642	0.6952	1	0.0093	0.2239	0.2365	0.0876	0.0227	0.0061
SSJ 1	0.0065	0.006	0.0105	0.0093	1	0.0849	0.007	0.0062	0.4394	0.0568
SSJ 2	0.1388	0.1219	0.2569	0.2239	0.0849	1	0.1527	0.1285	0.0667	0.0117
PL 1	0.5996	0.0823	0.0867	0.2365	0.007	0.1527	1	0.1879	0.0191	0.0055
PL 2	0.6576	0.4205	0.027	0.0876	0.0062	0.1285	0.1879	1	0.0177	0.0052
PZ 1	0.0183	0.0173	0.0243	0.0227	0.4394	0.0667	0.0191	0.0177	1	0.2022
PZ 2	0.0053	0.0051	0.0064	0.0061	0.0568	0.0117	0.0055	0.0052	0.2022	1

The statistical results obtained for *E. coli* removal are similar to those obtained for total coliform removal. The Pozzani filters performed significantly worse than all but the Stefani São João filters, which also performed poorly. Again, the differences in performance obtained by the AquaMaster, Doulton Super Sterasyl, and Pelikan filters are insignificant; *E. coli* removal by these brands is comparable. As stated in section 5.3.2, the *E. coli* removal efficiencies observed for the studied filters are related to pore size.

5.3.4 Discussion of Coliform Results Obtained at MIT

Pelikan filter number 2 showed the highest percent removal of total coliforms. This may be because this filter was new and had not been scrubbed like the other filters. The lower value for Stefani filter number 1 may be due to cracks near the top of the filter. These hairline cracks appeared on the top surface of the filter. Because a replacement filter was not available, water was added to just below the cracks to minimize contamination via this route. However, some water may have leaked through, resulting in the lower percent removal values observed for this filter when compared to its counterpart.

As can be seen from Figures 5.9 and 5.10, the AquaMaster and Pelikan filters performed well with regard to coliform removal. The Doulton also performed well. It is interesting to note that while the AquaMaster and Doulton Super Sterasyl filters both contain carbon and silver on their interiors, the Pelikan filters contain neither. Also, the worst performing filters, the Pozzanis, contain silver. Thus the higher coliform removals observed for these brands are likely due to pore size, versus the presence of silver. Although some filters appeared to perform better than the others, statistically, there is no difference between the AquaMaster, Doulton, and Pelikan filters. The Pozzanis performed significantly worse than these brands, but not significantly worse than the Stefani São João filter(s).

As observed for the Kenya data, the studied ceramic candle filters did not remove coliforms to the EPA's standard or WHO guidelines. Although the Pelikan and AquaMaster filters obtained zero total coliform and/or *E. coli* counts for several runs, the percent of samples testing positive for these bacteria was over 5%. Thus, under these criteria, the studied ceramic candle filters failed as water purifiers. However, it should be noted that the AquaMaster, Doulton, and Pelikan filters

removed over 98% of total coliforms and *E. coli*. Thus, they were successful in this regard. Ceramic water filtration may be best used in combination with other water treatment processes, such as chlorine or solar disinfection, if strict standards such as those outlined by the EPA are to be met.

5.4. Viral Removal

At MIT, tests using MS2 coliphages were performed on the Pelikan filters to determine viral removal efficiency. Results are given in section 5.4.1 and discussed in section 5.4.2.

5.4.1 Results of Viral Removal Studies Performed at MIT

At MIT, a total of five double agar layer tests were performed. Of these, only one test produced sound results. Reagent water spiked with MS2 coliphages was tested and compared to filtered water to determine viral removal. The concentration of spiked source for the one successful trial was around 7.4×10^8 PFU/mL. The concentration of MS2 coliphages in water filtered by Pelikan filter number 1 was 1.3×10^9 PFU/mL. The concentration of MS2 coliphages in water filtered by Pelikan filter number 2 was also 1.3×10^9 PFU/mL. The fact that filtered water contained more virus than unfiltered may reveal an error in the measurement of the source water. Regardless, these results suggest that the Pelikan filters are not capable of filtering out viruses from reagent water.

5.4.2 Discussion of Viral Removal Results Obtained at MIT

The results from the one successful viral removal assay are as expected. It was not believed that the Pelikan filter would be able to remove viruses, despite their successful performance with regard to bacteria. This is because the diameter of MS2 coliphages (0.025 μm) is about one-tenth the diameter of *E. coli*; and some *E. coli* were still making it through the filters (Earth, 2005). Additionally, reagent water was used on the filters. Reagent water contains no suspended particles or organics onto which viruses can adsorb. Thus using reagent water provided a worst-case scenario of viral removal. If Charles River water was used, then some viral removal may have been observed, as the viruses could have aggregated to form larger particles, which would subsequently be too large to pass through the filter pores.

Results from the one successful assay indicate that the Pelikans are unable to remove viruses from solution. These filters did not meet EPA standards of 99.99% removal of enteric viruses, nor did they meet the WHO recommendation that zero indicator microorganisms be present in a water supply.

The discrepancy in viral concentration observed between filtered and unfiltered water may be due to a variety of reasons. First of all, only 1 mL of water was sampled and tested. This small volume may not be reflective of the entire 2 L of water filtered by each Pelikan. If the unfiltered water was not thoroughly mixed, then this could explain why the filtered water appears to contain more viruses than the source water; the sample tested may not have been representative of the entire volume. Additionally, the water coming through the filter was only sampled once. In other words, it is possible that the viruses may have come through the filter in waves. Viruses may have

temporarily sorbed to the filter element and built up before all of a sudden exiting through the candle filter. Regardless of the discrepancy, the results support the hypothesis that the filters are not capable of removing viruses. However, these results are not definitive; many more tests need to be performed in order to obtain conclusive evidence on the ability of ceramic candle filters to remove viruses from solution.

During the course of four weeks, five double agar layer assays were performed. Of these, only one was successful. The first two tests utilized *E. coli* F_{amp} as the bacterial host. After both of the tests failed to produce plaques, the bacterial host was switched to *E. coli* C3000, per recommendation of Joe Brown. A doctoral student under Professor Mark Sobsey of the Department of Environmental Science and Engineering at UNC, Brown graciously provided instruction and relevant assistance during the performance of coliphage tests. According to Brown, this host was easier to work with and was more likely to produce successful results. Upon switching to this host, plaques were visible and the assay was successful. Subsequent tests utilized this host, but did not produce any data. The lack of success with the assay could be due to any number of factors, including temperature of the water bath, high shaking speed while incubating, etc. Unfortunately, when the same steps taken for the successful assay were repeated, the assay failed. Thus, the assay appears to be finicky. The only logical explanation (according to the author) for repetitive failure of the assay is described below.

Before running any tests, viruses were grown up and assayed to determine concentration of viral stock. This assay utilized *E. coli* F_{amp} as the bacterial host, and was successful in that plaques were obtained. However, only 1 mL of viral stock was assayed. This stock came from only a few of the twenty plates used to grow up viruses. In other words, the viral concentration determined in this assay was not representative of every plate of viruses. Thus some of the other plates may not have grown up viruses, resulting in an inconsistency with regard to viral concentration between test tubes storing stock. This discrepancy is the only reasonable explanation for why other assays did not work. If the stock used for the failed assays did not contain viruses, then this would explain why the filter performance assays failed.

5.5 Summary of Results

Table 5.17: Summary of Data Obtained for Each Brand of Filter Tested

	Turbidity Removal (%)		Flow Rate (L/hr)		Total Coliform Removal (%)		*E. coli* Removal (%)		
Filter	**Kenya**	**MIT**	**Kenya**	**MIT**	**Kenya**	**MIT**	**Kenya**	**MIT**	**Cost ($)**
AquaMaster	98.3	88.6	0.093	0.160	99.835	99.6	99.995	99.95	10.00
Doulton	98.3	92	0.235	0.546	99.831	99.0	99.993	99.7	40.00
Stefani	98.8	93.1	0.101	0.241	99.694	97.5	99.967	97.6	2.25
Pelikan	98.3	97.3	0.182	0.203	99.982	99.6	99.985	99.9	2.00
Pozzani	97.1	89.9	0.101	0.180	99.653	95.6	99.769	93	20.00

The above table provides a summary of the data obtained for each brand of filter tested (excluding viral results). According to this information, the Pelikan appears to perform the best for the cheapest price ($2). The Pelikan filters showed significantly better turbidity removal than

the other filters tested at MIT. These filters were also among the three brands that showed significantly better total coliform and E. coli removals than the Pozzani filters. The Doulton Super Sterasyl filters also performed well. These filters had the fastest flow rate, which was significantly faster than the other brands tested. The Doultons were also among the top three brands with regard to total coliform and E. coli removals. However, these filters are the most expensive, retailing for a price of approximately $40. The AquaMaster filters performed well with regard to total coliform and E. coli removal. However, the flow rates determined for these filters were not impressive, and the cost was intermediate at $10.

6. Conclusions and Recommendations

During the course of this study, the AquaMaster (Piedra Candle), Doulton Super Sterasyl, Stefani São João, Pelikan, and Pozzani candle filters were compared based on turbidity removal, flow rate, microbial removal, and cost. This chapter discusses the conclusions drawn from study results, and includes recommendations regarding filter usage.

6.1 Turbidity Removal Conclusions

The filters examined in this study were tested for turbidity removal. Turbidity results for individual filters were compared to EPA guidelines in order to determine filter efficacy. Study results in Kenya revealed that only Stefani São João filter number 2 reduced the level of turbidity (± standard deviation) to less than 0.3 NTU, the value below which the EPA requires 95% of daily treated water samples to fall. All other filters reduced turbidity to below 1 NTU on average. Study results at MIT revealed that the Pelikan filters performed significantly better than all filters but Stefani São João filter number 2. The Pelikans reduced turbidity of Charles River water to below the EPA recommended value of 0.3 NTU. As in Kenya, other filters tested at MIT reduced turbidity to below 1 NTU on average. None of the filters reduced turbidity to below the WHO recommended value of 0.1 NTU.

Out of the filters studied, the Pelikan filters performed the best at removing turbidity from Charles River water. The good performance of Stefani São João filter number 2 may reveal that this brand of filter was not appropriately represented in this study. Stefani São João filter number 1 possessed visible hairline cracks near the top of the filter, which were noticed upon return to MIT. This filter performed much poorer than its counterpart. Thus results of this study may not be indicative of the typical performance of this brand. More studies need to be conducted in order to discern the ability of Stefani São João filters to remove turbidity.

Results of turbidity removal studies indicate that the Pelikan is the most effective filter at removing turbidity from polluted water.

6.2 Flow Rate Conclusions

The aforementioned filters were also compared based on flow rate. Flow rates were compared to the minimum daily requirement of water for an individual (7.5 L) in order to determine filter efficacy (Howard, 2004). Results obtained in Kenya (utilizing the polluted Nairobi source) reveal that none of the filters were able to produce this amount of water in one day. Even the Doulton Super Sterasyl, which possessed the fastest flow rate (0.235 L/hr), could only filter a maximum of 4.8 L of Nairobi water per day.

Flow rate tests performed using Charles River water were not as slow, given the lower turbidity of Charles River water. As in Kenya, the Doulton Super Sterasyl possessed the greatest flow rate (0.546 L/hr) of the studied filters; it performed significantly better than the other brands. At this rate, the Doulton can filter 13.1 L of water per day, enough for two people (for the WHO-specified minimum volume). This prediction assumes that the flow rate does not decline over

time. Unlike studies performed in Kenya, at MIT only one flow rate determination was made per run. Thus it was not studied whether or not flow rate will decrease over time. However, intuitively, one would predict that flow rate would decline as more and more particles build up on the surface of the filter element and clog the filter.

Overall, the Doulton Super Sterasyl possessed the greatest flow rate out of the studied filters.

6.3 Coliform Removal Conclusions

Filters were tested for total coliform and *E. coli* removal. The results for filtered water were compared to EPA standards and WHO guidelines to determine filter efficacy. Although results obtained in Kenya and at MIT revealed that the filters were able to significantly reduce the amount of coliform contamination present in the water, none of the filters achieved the WHO guideline recommendation (zero indicator organisms) or the EPA standard, which requires that no more than 5% of total water sampled monthly test positive for total coliforms. Although several filters removed all coliforms and *E. coli* for certain runs, the removal was not less than 5% over all the runs. Thus, under these criteria, the studied ceramic candle filters failed as water purifiers.

Overall, the Pelikan, Doulton, and AquaMaster filters performed significantly better than the Pozzani filters at removing total coliforms and *E. coli*.

6.4 Viral Removal Conclusions

The Pelikan filters were tested for removal of MS2 coliphages. Results from the one successful assay indicated that these filters were unable to remove viruses from solution. Thus they did not meet EPA standards of 99.99% removal of enteric viruses, nor did they meet the WHO recommendation that zero indicator microorganisms be present in a water supply. Thus, the Pelikan filters are not able to remove viruses from drinking water.

6.5 Cost

Of the studied filters, the Doulton Super Sterasyl was the most expensive, retailing for $40. The Pozzani was the second most expensive, retailing in the U.S. for $20. The price of the AquaMaster was intermediate at $10. The Stefani São João filters were a cheap $2.25. The Pelikans were the cheapest filters, available in Kenya for $2.

6.6 Recommendations

Out of all the filters studied, the Pelikan candle filters performed the best. The Pelikan filters possessed the greatest turbidity removal at MIT and showed high total coliform and *E. coli* removals. These filters also had the second fastest flow rate in Kenya. Surprisingly, this brand was also the cheapest, retailing for $2 in Nairobi. The performance and affordability of this filter as a water purifier is good news for people in developing countries. However, despite the impressive performance of the Pelikan, the author recommends ceramic candle filtration as only one step in the water-purifying process. Highly turbid waters, such as the Nairobi river water used in this study, should be treated pre-filtration. Sedimentation in a safe storage vessel or coagulation are two possible treatment options capable of reducing suspended particles. Upon removal of

larger particles, flow rate will increase and a greater volume of water will be produced. However, if water is not turbid, as was the case with Charles River water, this step is unnecessary.

Additionally, the author recommends that the water level be as high above the filter as possible (i.e., fill to the top of the container). If the water level is higher, more water will be filtered due to the greater pressure (See Appendix A). A recommendation is also made to manufacturers to make and distribute longer filters. Filter surface area is related to flow rate, and so longer filters will be capable of faster flow rates. This was observed in Kenya, where data indicated that flow rate was proportional to candle length. Another possible option for increasing volume of filtered water entails buying more filters. For example, households could place multiple candles in one container to achieve a higher flow rate.

The results of the coliform removal study indicate that water filtration may be only one step in the water treatment process. It is recommended that water be treated post-filtration to remove any residual microbial contamination. For example, chlorine disinfection and solar disinfection are two possible options.

Although ceramic candle filtration is not 100% effective as a water purifier, results from this study show that it can be an integral step in the attainment of a sufficient volume of clean, safe drinking water.

6.7 Final Comments

Despite the failure of the filters to meet several of the EPA standards and WHO guidelines, it should be noted that these filters immensely improved the quality of water subjected to treatment. In Kenya, data indicated that up to four and five logs of total coliforms and *E. coli* were removed from the polluted Nairobi source. Concomitantly, the turbidity was also greatly reduced by filtration (up to 99% in Kenya). Thus the EPA standards, although helpful, may not be completely appropriate with regard to evaluating the ability of ceramic candle filters to purify water, especially in the context of developing nations. It should be noted that WHO states that their guidelines are not mandatory limits; rather they recommend that the guidelines be considered in the context of the local setting (WHO, 2004). Additionally, WHO states that "implementation of a water quality intervention that results in an estimated health gain of more than 5% would be considered extremely worthwhile (WHO, 2004)." Studies have already been performed that show filtration to reduce endemic diarrheal disease by 40% (Clasen et. al, 2004). Thus, for people living in developing countries, ceramic water filtration can greatly increase the quality of their drinking water and their quality of life. If paired with sedimentation/coagulation and disinfection, ceramic water filtration can even produce EPA-worthy drinking water.

The results from this study indicate that the Pelikan filter, which is available for only $2 at the Nakumatt market in Nairobi, is a viable option for improving drinking water quality.

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Appendix A: Explanation of Darcy's Law

Flow rate of a ceramic water filter ultimately depends on several variables, including porosity, thickness, and area of the filter element; density and viscosity of the water flowing through; gravity; and height of water above the filter (hydraulic head). All of these variables can be related to flow rate through Darcy's Law, which is expressed as $Q = K \bullet (dh/dl) \bullet A$, where Q is the flow rate (length^3/time); K is the proportionality coefficient or "hydraulic conductivity" (length/time); h is the change in hydraulic head (length); dl is the distance over which the change in head occurs (length); and A is the area of flow (length^2) (Harvey notes, 2004).

The hydraulic conductivity (K) relates to the ability of a fluid to flow through a medium (porous ceramic filter in this case). K depends on the intrinsic permeability of the medium, the density of the fluid, the dynamic viscosity of the fluid, and gravity. This relationship is expressed as $K = (k\rho g/\mu)$, where k is the intrinsic permeability (length^2), ρ is the fluid density (mass/length^3), g is gravity (length/time^2), and μ is fluid viscosity (mass/[length•time]). The intrinsic permeability (k) is a property of the medium. In this case, k relates to the porosity of the ceramic water filters. A filter with many large pores will have a greater hydraulic conductivity (K) and thus a greater flow rate. A filter with tiny pores will have a lower K and thus a slower flow rate because there is less space for the water to flow through.

The rate of fluid flow through a filter is also dependent on the change in hydraulic head (dh) over a given distance (dl). The hydraulic head (h) relates to the pressure pushing water through the medium. This pressure increases with increasing elevation of water over the top of the filter element. Thus when the water level is low, h is smaller than when the water level is several inches above the filter element. The distance over which the change in head occurs (dl) is the thickness of the filter element. Thus, with all other variables held constant, thick-shelled filters will have slower flow rates than thin-shelled filters.

Finally, flow rate is dependent on the area through which the fluid flows. The area of flow is the surface area of the filter (A), which is dependent on filter height (h_f) and diameter (d_f). With other variables held constant, filters with a greater surface area will have more space for the water to flow through, resulting in a greater rate of flow.

For a mathematical derivation relating the above parameters to flow rate through candle or disk filters, refer to *Development of a Ceramic Water Filter for Nepal* by Robert Dies (Dies, 2003).

Appendix B: Graphs of Pore Size Distribution in Various Ceramic Candle Filters (Bershteyn et al., 2005)

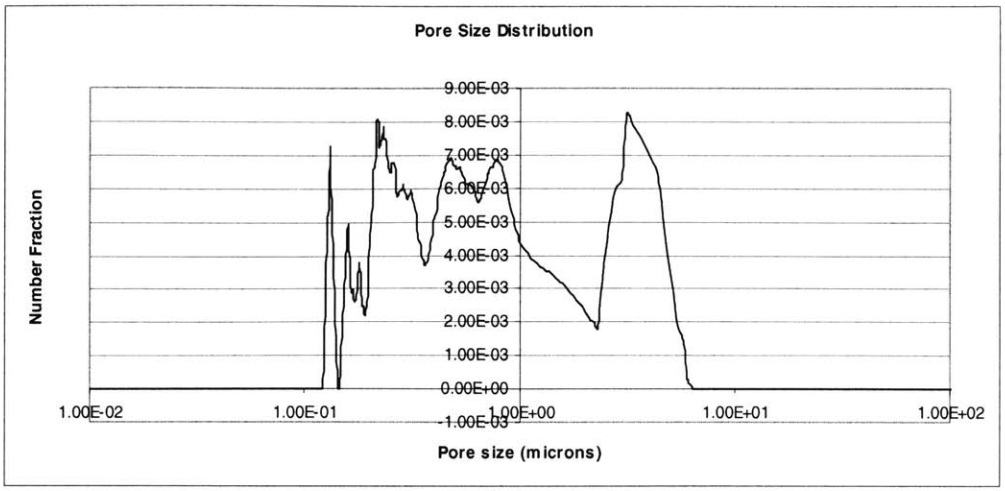

Figure B.1: Pore Size Distribution for Katadyn Candle Filter

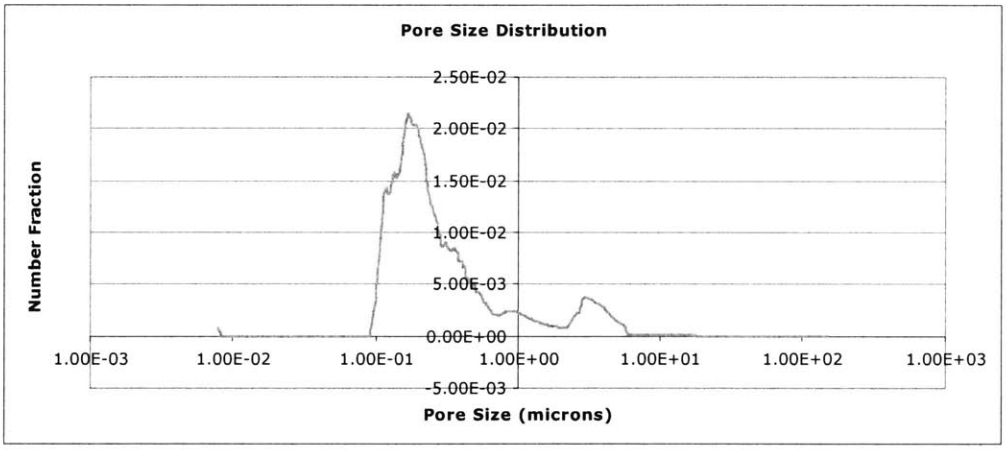

Figure B.2: Pore Size Distribution for Pelikan Candle Filter

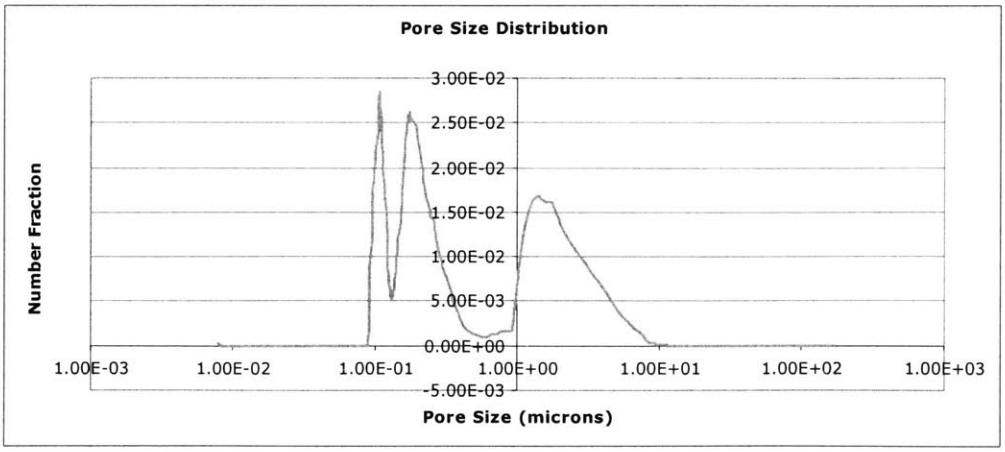

Figure B.3: Pore Size Distribution for Doulton Super Sterasyl Candle Filter

Appendix C: Characteristics of Tap Water Used to Dilute Source Water in Kenya

Central Water Testing Laboratories
PHYSICAL/CHEMICAL WATER ANALYSIS REPORT

PARAMETERS	UNIT	RESULTS	
PH	pH Scale	7.5	
Color	mgPt/l	<5	
Turbidity	N.T.U.	4.6	
Permanganate Value (20 min. boiling)	mgO_2/l	<0.4	
Conductivity (25^0 C)	µS/cm	85.3	
Iron	mgFe/l	0.07	
Manganese	mgMn/l	<0.01	
Calcium	mgCa/l	5.6	
Magnesium	mgMg/l	1.46	
Sodium	mgNa/l	10.05	
Potassium	mgK/l	1.6	
Total Hardness	$mgCaCO_3/l$	20	
Total Alkalinity	$mgCaCO_3/l$	28	
Chloride	mgCl/l	2	
Fluoride	mgF/l	0.16	
Nitrate	mgN/l	2.65	
Nitrite	mgN/l	<0.01	
Ammonia	mgN/l	-	
Total Nitrogen	mgN/l	-	
Sulphate	$mgSO_4/l$	3.11	
Orthophosphate	mgP/l	-	
Total Suspended Solids	mg/l	-	
Free Carbon Dioxide	$mgCO_2/l$	4	
Dissolved Oxygen	mgO_2/l	-	
Total Dissolved Solids	mg/l	53	
Lead	mgPb/l	0.00	

This information was kindly provided by Jackson Kingori of the Ministry of Water's Pollution Control Division.

Appendix D: List of Supplies Brought to Kenya from U.S.

Quantity	Description	Company	Catalog#
Miscellaneous Items			
4	Pozzani ceramic candle filters	Pozzani	
4	Doulton Super Sterasyl ceramic candle filters	Doulton	
1	Diamond Grip Latex Gloves		
1	1-L Nalgene bucket		
1	O-rings for Filter Unit Assembly (5/pk)	Millipore	
1	Razor blade		
1	Lighter		
Sample Collections			
1	Travel Cooler and Ice packs to transport	CVS	
3	Whirlpack bags-100ml-100/pk	VWR	11216-759
0.1	Lab marking pens (permanent), extra fine tip 10/pk	VWR	52877-140
0.125	Lab Labeling Tapes, rainbow pack of 16, 3/4 inch width	VWR	36425-025
200	Sterile plastic pipette tips		
2	Automatic Pipette, autoclave 1-5 ml	Oxford	53502-440
Turbidity			
1	Portable Turbidimeter Model 2100 P	HACH	
1	20 NTU Formazin Turbidity Std.	HACH	
6	Clear glass vials		
6	AA Batteries for turbidimeter		
Membrane Filtration			
2	Filter Unit Assemblies	Millipore	xx6300120
2	1/8 in viton tubing for vacuum	Millipore	XX6504710
1	Hand pump	VWR	6131-0020
0.25	S-Pak Filters 0.45 um 47 mm 1000/Pk	Millipore	HAWGO47S1
5	m-ColiBlue 24 Broth 50/Pk	Millipore	MOOPMCB24
1	petri dishes with pads 500/Pk	Millipore	PD10047S5
2	Filter Forceps, Pall Gelman	VWR	30033-042

Appendix E: Statistical T-Test Used to Analyze Data

The statistical t-test formula in Microsoft Excel was used to analyze data and compare filters. Filters of the same brand were submitted to the homoscedastic t-test as they were expected to have similar values. Comparisons between different brands of filters utilized the heteroscedastic t-test. The follow information was taken directly from Microsoft Excel Help.

Quoting Microsoft Excel Help:

T-TEST

Returns the probability associated with a Student's t-Test. Use TTEST to determine whether two samples are likely to have come from the same two underlying populations that have the same mean.

Syntax

TTEST(array1,array2,tails,type)

Array1 is the first data set.
Array2 is the second data set.
Tails specifies the number of distribution tails. If tails = 1, TTEST uses the one-tailed distribution. If tails = 2, TTEST uses the two-tailed distribution.[3]
Type is the kind of t-Test to perform.

If type equals	This test is performed
1	Paired
2	Two-sample equal variance (homoscedastic)
3	Two-sample unequal variance (heteroscedastic)

[3] The two-tailed distribution was used for analysis.

Appendix F: List of Materials and Supplies Used for Membrane Filtration Test

Quantity	Description	Company	Catalog#
Miscellaneous Items			
1	Ethanol		
1	Methanol		
10	Sterile graduated cylinders		
1	Razor blade		
1	Lighter		
Incubation			
1	Thermometer (-10 to 100oC)	HACH	2676300
1	Single Chamber Incubator (230V)	Millipore	xx631K230
1	Power supply (230V)	Millipore	FTPFO4947
Sample Collections			
1	Travel Cooler (or refrigerator) and Ice packs to transport	CVS	
4	Whirlpack bags-100ml-100/pk	VWR	11216-759
0.1	Lab marking pens (permanent), extra fine tip 10/pk	VWR	52877-140
200	Sterile plastic pipette tips		
2	Automatic Pipette, autoclave 1-5 ml	Oxford	53502-440
Membrane Filtration			
3	Filter Unit Assemblies	Millipore	xx6300120
3	1/8 in viton tubing for vacuum	Millipore	XX6504710
1	Hand pump	VWR	6131-0020
0.5	S-Pak Filters 0.45 um 47 mm 1000/Pk	Millipore	HAWGO47S1
10	m-ColiBlue 24 Broth 50/Pk	Millipore	MOOPMCB24
1	petri dishes with pads 500/Pk	Millipore	PD10047S5
1	Filter Forceps, Pall Gelman	VWR	30033-042

Appendix G: Materials and Equipment for Detection and Enumeration of F-RNA Coliphages

Quantity	Description	Company	Catalog #
Incubation			
1	Incubator capable of operating at 35°C ± 1°C	Precision Scientific	
1	Incubator capable of operating at 37°C ± 1°C	VWR Scientific	1555
1	Water bath capable of operating at 45°C	MT Lauda	M30013
1	Orbit shaker (in an incubator)		
1	Big Bill Thermolyne shaker (in an incubator)		
2	Thermometers (0-100°C)	VWR Scientific	61019-034
Sample Collection and Dilutions			
23	Sterile 1.5-mL microcentrifuge tubes for water collection	USA Scientific	MI 1415
40	Sterile 16 x 150 mm glass dilution tubes with screw caps		
2	Test tube rack		
4	Sterile serological pipettes (10 mL)	Corning Incorporated	4488
4	Sterile serological pipettes (25 mL)	Corning Incorporated	4489
1	Adjustable 2-20 µL micropipetter	Eppendorf Research	226574
1	Adjustable 20-200 µL micropipetter	Eppendorf Research	246566
1	Adjustable 100-1000 µL micropipetter	Eppendorf Research	253513
Media and Culture Preparation			
40	100 x 15 mm polystyrene, disposable, sterile, stackable petri dishes	VWR Scientific	25384-094
1	Bunsen burner		
1	Sterile inoculation loops		
2	Autoclavable 100-mL or 1-L wide-mouth glass bottles with screw caps		
2	1-L and 2-L sterile Erlenmeyer flasks		
1	Stir plate (and stir bar)	VWR Scientific	325
1	Spectrophotometer (visible range)	Beckman	640
1	1-cm cuvettes		
4	125 and 250-mL sterile fluted-Erlenmeyer shaker flasks with caps/plugs		
2	Weigh boats		
1	Precision standard balance (up to 200 g) with 0.1 mg accuracy	Ohaus	TS-400S
several	100, 250, and 1000-mL graduated cylinders		
1	Autoclave	Consolidated Stills & Sterilizers	
10	Blue Max Jr. 15-mL polystyrene conical tube, 17 x 120 mm	Falcon	35-2095
1	Acrodisc 25 mm syringe filter with 0.2 µm HT Tuffryn Membrane	Pall Corporation	PN 4192
1	Vortexer 2: Vortex Genie 2	VWR Scientific	
	Ice		
Miscellaneous			
1	Powder-free latex exam gloves	Kimberly-Clark	330
1	pH meter	Corning Incorporated	220
1	KimWipes EX-L	Kimberly-Clark	

Bacteria and Virus Stock

1	MS2 (F-RNA) stock coliphage	UNC	
1	*E. coli* F_{amp} host stock (picks up male-specific phages like MS2)	UNC	
1	*E. coli* C3000 host stock (picks up male-specific and somatic phages)	UNC	

Nutrients and Chemicals

varies	Bacto Agar	Becton Dickinson & Co.	214010
30 g	Bacto Tryptic Soy Broth: Soybean-Casein Digest Medium	Becton Dickinson & Co.	211823
	Glycerol	Mallinckrodt AR	5092
4 g	Sodium Chloride	Mallinckrodt AR	7544
0.1 g	Potassium Chloride	Mallinckrodt AR	6858
0.72 g	Sodium Phosphate	EM Science	7558-79-4
0.24	Potassium Dihydrogen Phosphate	Mallinckrodt AR	7100-03
0.15 g	Ampicillin Sodium Salt	Shelton Scientific, Inc.	3A0450
0.15 g	Streptomycin Sulfate	Sigma-Aldrich	S-9137
	70% Ethanol		
	Bleach		
	Reagent Water		

Appendix H: Data

Key:

1	AquaMaster 1
2	AquaMaster 2
3	Doulton Super Sterasyl 1
4	Doulton Super Sterasyl 2
5	Stefani Sao Joao 1
6	Stefani Sao Joao 2
7	Pelikan 1
8	Pelikan 2
8b	Pelikan 2b (replaced #8 when it broke)
9	Pozzani 1
10	Pozzani 2
Red Colony	Number of Red Colonies
E. coli	Number of E. coli Colonies
A	Sample A
B	Sample B
TC	Total Coliform
EC	E. coli

Results from Turbidity and Flow Rate Studies Performed in Kenya:

13-Jan-05 **14-Jan-05**

		Turbidity after Three Hours (NTU)				Turbidity			Turbidity after Twenty Hours (NTU)					Turbidity	
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)		Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.37	0.34	0.36	0.36	0.27	98.22	0.138		0.4	0.41	0.4	0.40	0.31	97.95	0.037
2	0.43	0.36	0.37	0.39	0.30	98.01	0.13		0.31	0.28	0.28	0.29	0.19	98.71	0.039
3	0.24	0.22	0.22	0.23	0.14	99.09	0.423		0.4	0.39	0.49	0.43	0.33	97.79	0.096
4	0.53	0.53	0.57	0.54	0.45	96.97	0.357		0.38	0.36	0.37	0.37	0.27	98.17	0.11
5	0.21	0.24	0.21	0.22	0.13	99.13	0.16		0.42	0.3	0.26	0.33	0.23	98.46	0.045
Blank:	0.08	0.08	0.11	0.09	0.00				0.13	0.08	0.08	0.10	0.00		
Source:	15.5	15.3	14.3	15.03	14.94				15.5	15.3	14.3	15.03	14.94		

14-Jan-05 **14-Jan-05**

		Turbidity after Three Hours (NTU)				Turbidity			Turbidity after Twenty Hours (NTU)					Turbidity	
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)		Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
6	0.13	0.16	0.29	0.19	0.13	99.22	0.124		0.19	0.2	0.25	0.21	0.13	99.24	0.04
7	0.22	0.22	0.2	0.21	0.15	99.10	0.158		0.34	0.36	0.49	0.40	0.31	98.16	0.06
8	0.21	0.2	0.21	0.21	0.15	99.14	0.169		0.17	0.18	0.19	0.18	0.10	99.43	0.09
9	0.24	0.24	0.23	0.24	0.18	98.96	0.1		0.25	0.31	0.32	0.29	0.21	98.77	0.035
10	0.37	0.39	0.39	0.38	0.32	98.10	0.085		0.38	0.36	0.4	0.38	0.30	98.26	0.046
Blank:	0.06	0.06	0.06	0.06	0.00				0.09	0.08	0.08	0.08	0.00		
Source:	18.3	15.7	17.3	17.10	17.04				18.3	15.7	17.3	17.10	17.02		

17-Jan-05 **18-Jan-05**

		Turbidity after Three Hours (NTU)				Turbidity			Turbidity after Twenty Hours (NTU)					Turbidity	
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)		Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.72	0.73	0.74	0.73	0.66	97.88	0.143		0.56	0.51	0.51	0.53	0.45	98.54	0.042
2	0.64	0.65	0.66	0.65	0.58	98.13	0.161		0.49	0.48	0.49	0.49	0.41	98.67	0.048
3	0.56	0.54	0.58	0.56	0.49	98.42	0.34		0.34	0.34	0.39	0.36	0.28	99.09	0.104
4	0.9	0.83	0.8	0.84	0.77	97.51	0.35		0.43	0.37	0.41	0.40	0.33	98.94	0.1
5	0.81	0.68	0.71	0.73	0.66	97.87	0.13		0.86	0.86	0.86	0.86	0.79	97.47	0.042
Blank:	0.07	0.07	0.07	0.07	0.00				0.07	0.08	0.07	0.07	0.00		
Source:	43.5	26.3	23.7	31.17	31.10				43.5	26.3	23.7	31.17	31.09		

18-Jan-05 **18-Jan-05**

		Turbidity after Three Hours (NTU)				Turbidity			Turbidity after Twenty Hours (NTU)					Turbidity	
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)		Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
6	0.2	0.22	0.19	0.20	0.10	99.44	0.216		0.33	0.22	0.23	0.26	0.15	99.21	0.053
7	0.64	0.65	0.65	0.65	0.55	97.05	0.454		0.6	0.71	0.55	0.62	0.51	97.26	0.057
8	0.55	0.53	0.52	0.53	0.43	97.66	0.374		0.39	0.32	0.32	0.34	0.23	98.76	0.095
9	1.2	1.1	1.08	1.13	1.03	94.46	0.188		0.46	0.47	0.48	0.47	0.36	98.07	0.042
10	1.53	1.51	1.51	1.52	1.42	92.36	0.26		0.58	0.54	0.58	0.57	0.45	97.55	0.051
Blank:	0.11	0.09	0.1	0.10	0.00				0.09	0.11	0.14	0.11	0.00		
Source:	19.6	17.8	18.5	18.63	18.53				19.6	17.8	18.5	18.63	18.52		

Results from Turbidity and Flow Rate Studies Performed at MIT:

Tap Water Flow Rate (L/hr)			
Filter	Sample 1	Sample 2	Avg
1	0.11	0.129	0.120
2	0.492	0.391	0.442
3	0.99	1.173	1.082
4	1.606	1.353	1.480
5	2.358	1.276	1.817
6	0.936	0.709	0.823
7	0.38	0.409	0.395
8b	0.23	0.227	0.229
9	1.588	0.813	1.201
10	0.44	0.728	0.584

crack?

12-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.51	0.61	0.53	0.55	0.41	93.15	0.256
2	0.71	0.87	0.6	0.73	0.59	90.19	0.332
3	0.81	0.61	0.58	0.67	0.53	91.20	0.759
4	0.45	0.58	0.57	0.53	0.39	93.43	0.929
5	0.26	0.26	0.37	0.30	0.16	97.38	0.434
6	0.15	0.24	0.11	0.17	0.03	99.55	0.443
7	0.21	0.26	0.18	0.22	0.08	98.72	0.346
8b	0.18	0.27	0.16	0.20	0.06	98.94	0.16
9	1.55	1.51	1.45	1.50	1.36	77.21	0.15
10	1.61	1.51	1.49	1.54	1.40	76.66	0.088
Blank:	0.13	0.13	0.16	0.14	0.00		
Source:	6.07	6.69	5.61	6.12	5.98		

14-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.5	0.47	0.44	0.47	0.37	95.61	0.17
2	0.67	0.57	0.57	0.60	0.50	94.02	0.249
3	0.31	0.33	0.5	0.38	0.28	96.68	0.395
4	0.67	0.63	0.6	0.63	0.53	93.67	0.725
5	0.37	0.36	0.38	0.37	0.27	96.79	0.41
6	0.26	0.28	0.17	0.24	0.14	98.38	0.282
7	0.19	0.16	0.27	0.21	0.11	98.73	0.3
8b	0.11	0.15	0.33	0.20	0.10	98.85	0.155
9	0.71	0.65	0.69	0.68	0.58	93.07	0.282
10	0.87	0.91	1	0.93	0.83	90.19	0.297
Blank:	0.09	0.1	0.11	0.10	0.00		
Source:	8.54	8.62	8.41	8.52	8.42		

16-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.43	0.53	0.66	0.54	0.45	87.13	0.038
2	0.53	0.54	0.43	0.50	0.41	88.28	0.123
3	0.4	0.36	0.35	0.37	0.28	92.03	0.263
4	0.29	0.28	0.28	0.28	0.19	94.52	0.376
5	0.32	0.38	0.39	0.36	0.27	92.22	0.212
6	0.21	0.21	0.19	0.20	0.11	96.83	0.157
7	0.18	0.17	0.22	0.19	0.10	97.21	0.201
8b	0.19	0.18	0.19	0.19	0.09	97.31	0.096
9	0.37	0.36	0.37	0.37	0.27	92.12	0.079
10	0.51	0.56	0.6	0.56	0.46	86.65	0.087
Blank:	0.1	0.05	0.13	0.09	0.00		
Source:	4.17	3.38	3.14	3.56	3.47		

Water level was at 3/4 the filter height for all the filters (explains slowness)

Results from Turbidity and Flow Rate Studies Performed at MIT (continued):

18-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.69	0.63	0.61	0.64	0.53	92.08	0.145
2	0.53	0.61	0.49	0.54	0.43	93.59	0.194
3	0.42	0.38	0.38	0.39	0.28	95.84	0.357
4	0.58	0.54	0.51	0.54	0.43	93.59	0.617
5	0.53	0.54	0.54	0.54	0.42	93.69	0.188
6	0.29	0.35	0.3	0.31	0.20	97.04	0.195
7	0.28	0.26	0.26	0.27	0.15	97.75	0.27
8b	0.36	0.29	0.38	0.34	0.23	96.59	0.145
9	0.32	0.3	0.27	0.30	0.18	97.29	0.222
10	0.8	0.79	0.77	0.79	0.67	89.93	0.117
Blank:	0.1	0.12	0.13	0.12	0.00		
Source:	6.33	7.15	6.83	6.77	6.65		

22-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.4	0.36	0.42	0.39	0.28	90.28	0.16
2	0.34	0.36	0.3	0.33	0.22	92.36	0.189
3	0.24	0.3	0.33	0.29	0.18	93.87	0.479
4	0.41	0.32	0.31	0.35	0.23	91.90	0.552
5	0.22	0.2	0.37	0.26	0.15	94.79	0.241
6	0.28	0.19	0.14	0.20	0.09	96.88	0.202
7	0.22	0.16	0.17	0.18	0.07	97.57	0.318
8b	0.19	0.13	0.16	0.16	0.05	98.38	0.145
9	0.2	0.19	0.17	0.19	0.07	97.45	0.277
10	0.28	0.37	0.19	0.28	0.17	94.21	0.242
Blank:	0.12	0.13	0.09	0.11	0.00		
Source:	2.8	3.32	2.86	2.99	2.88		

24-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.3	0.32	0.34	0.32	0.18	90.24	0.097
2	0.27	0.26	0.44	0.32	0.18	90.05	0.127
3	0.3	0.22	0.18	0.23	0.09	94.94	0.221
4	0.27	0.29	0.34	0.30	0.16	91.32	0.498
5	0.34	0.28	0.26	0.29	0.15	91.68	0.187
6	0.27	0.24	0.24	0.25	0.11	94.03	0.145
7	0.19	0.32	0.15	0.22	0.08	95.66	0.229
8b	0.15	0.29	0.16	0.20	0.06	96.75	0.148
9	0.3	0.34	0.32	0.32	0.18	90.24	0.23
10	0.32	0.38	0.33	0.34	0.20	88.97	0.226
Blank:	0.14	0.15	0.13	0.14	0.00		
Source:	2	1.96	1.99	1.98	1.84		

26-Feb-05

	Turbidity (NTU)							
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)	
1	0.72	0.77	0.72	0.74	0.61	77.16	0.021	
2	0.52	0.38	0.41	0.44	0.31	88.46	0.047	
3	0.27	0.29	0.22	0.26	0.13	95.11	0.2	
4	0.23	0.22	0.3	0.25	0.12	95.48	0.2	
5	0.42	0.4	0.39	0.40	0.27	89.71	0.134	
6	0.4	0.4	0.4	0.40	0.27	89.84	0.112	
7	0.17	0.16	0.15	0.16	0.03	98.87	0.145	
8b	0.13	0.14	0.16	0.14	0.01	99.50	0.112	
9	0.35	0.35	0.35	0.35	0.22	91.72	0.078	Cleaned filters
10	0.44	0.36	0.29	0.36	0.23	91.22	0.071	after this run
Blank:	0.13	0.13	0.13	0.13	0.00			
Source:	2.21	2.55	3.63	2.80	2.66			

Results from Turbidity and Flow Rate Studies Performed at MIT (continued):

28-Feb-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.43	0.53	0.48	0.48	0.38	81.14	0.165
2	0.61	0.55	0.66	0.61	0.50	74.79	0.137
3	0.44	0.56	0.52	0.51	0.40	79.80	0.767
4	0.38	0.41	0.46	0.42	0.31	84.31	0.928
5	0.42	0.34	0.33	0.36	0.26	86.98	0.339
6	0.29	0.31	0.26	0.29	0.18	90.82	0.226
7	0.24	0.15	0.22	0.20	0.10	94.99	0.263
8b	0.25	0.29	0.21	0.25	0.15	92.65	0.15
9	0.17	0.19	0.14	0.17	0.06	96.83	0.201
10	0.53	0.29	0.31	0.38	0.27	86.31	0.262
Blank:	0.09	0.1	0.12	0.10	0.00		
Source:	2.26	1.87	2.17	2.10	2.00		

7-Mar-05

	Turbidity (NTU)						
Filter	Sample 1	Sample 2	Sample 3	Avg.	Avg.-Blank	% Removal	Flow Rate (L/hr)
1	0.47	0.41	0.42	0.43	0.36	87.53	0.218
2	0.42	0.45	0.4	0.42	0.35	87.87	0.214
3	0.46	0.37	0.33	0.39	0.32	89.13	0.844
4	0.36	0.4	0.39	0.38	0.31	89.24	0.723
5	0.47	0.57	0.52	0.52	0.45	84.55	0.226
6	0.7	0.43	0.45	0.53	0.46	84.32	0.212
7	0.21	0.18	0.19	0.19	0.12	95.77	0.273
8b	0.17	0.15	0.28	0.20	0.13	95.54	0.182
9	0.42	0.29	0.28	0.33	0.26	91.08	0.182
10	0.42	0.63	0.38	0.48	0.41	86.04	0.15
Blank:	0.03	0.08	0.1	0.07	0.00		
Source:	2.4	2	4.55	2.98	2.91		

Results from Coliform Removal Studies Performed in Kenya:

NOTE: Total coliform count equals the number of Red Colonies plus the number of E. coli colonies
NOTE: All counts are per 100 mL sample

Bacterial Removal Kenya Trial 1, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	35	6	41	49	2	51	46	4	99.997	100.00
2	4		4	39	6	45	24.5	3	99.998	100.00
3	242	32	274	282	42	324	299	37	99.981	99.99
4	35	14	49	46	13	59	54	13.5	99.997	100.00
5	149	83	232	333	234	567	399.5	158.5	99.975	99.97
6	1		1			0	0.5	0	100.00	100.00
7			0			0	0	0	100.00	100.00
8	290	10	300	287	7	294	297	8.5	99.62	99.96
9	334	78	412	138	6	144	278	42	99.64	99.82
10	495	95	590	411	243	654	622	169	99.20	99.28
		E. coli	Total							
Source for 1-5		610000	1605000							
Source for 6-7		31,675	84,125							
Source for 8-10		23500	77500							

Bacterial Removal Kenya Trial 2, 2005

	Red Colony A	E. coli A	Total Colifrom A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC rem
1	720	120	840	720	120	840	840	120	99.672	99.99
2	720	120	840	720	120	840	840	120	99.672	99.99
3	720	120	840	720	120	840	840	120	99.672	99.99
4	720	120	840	720	120	840	840	120	99.672	99.99
5	2000	1000	3000	2000	1000	3000	3000	1000	98.828	99.92
6	33	11	44			0	22	5.5	99.97	99.98
7	7	4	11	15	5	20	15.5	4.5	99.98	99.98
8	2	2	4			0	2	1	100.00	100.00
9	4	1	5	28	7	35	20	4	99.97	99.98
10	300	5	305	11		11	158	2.5	99.80	99.99
			0							
Source for 1-5		1210000	256000							
Source for 6-10		23,500	77,500							

Results from Coliform Removal Studies Performed at MIT:

Bacterial Removal February 12, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	3		3	2		2	2.5	0	99.85	100.00
2			0			0	0	0	100.00	100.00
3	28	1	29	12		12	20.5	0.5	98.78	99.52
4	30		30	40		40	35	0	97.92	100.00
5	26	1	27	38	2	40	33.5	1.5	98.01	98.57
6	16	2	18	5	1	6	12	1.5	99.29	98.57
7	10		10	5	1	6	8	0.5	99.52	99.52
8			0			0	0	0	100.00	100.00
9	75	9	84	96	17	113	98.5	13	94.14	87.62
10	75	10	85	106	32	138	111.5	21	93.36	80.00
				Actual	Actual	Actual				
1:100 Source	17	1	18	1700	100	1800				
1:100 Source	18	1	19	1800	100	1900				
1:20 Source	75	5	80	1500	100	1600				
1:20 Source	65	6	71	1300	120	1420				
Average				1575	105	1680				

	Bacterial Removal February 14, 2005									
	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	11		11	8		8	9.5	0	99.37	100.00
2	6		6	9		9	7.5	0	99.50	100.00
3	11		11	11		11	11	0	99.27	100.00
4	15		15	16		16	15.5	0	98.97	100.00
5	86	4	90	158	4	162	126	4	91.60	98.00
6	15		15	6		6	10.5	0	99.30	100.00
7	30		30	35		35	32.5	0	97.83	100.00
8	7		7	15	1	16	11.5	0.5	99.23	99.75
9	90	10	100	63	6	69	84.5	8	94.37	96.00
10	106	9	115	102	9	111	113	9	92.47	95.50
				Actual	Actual	Actual				
1:100 Source	8	1	9	800	100	900				
1:100 Source	18	3	21	1800	300	2100				
Average				1300	200	1500				

Bacterial Removal February 16, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	70	2	72	17		17	44.5	1	97.38	99.33
2	22		22	5		5	13.5	0	99.21	100.00
3	43	1	44	32		32	38	0.5	97.76	99.67
4	54	3	57	27		27	42	1.5	97.53	99.00
5	54	2	56	65	2	67	61.5	2	96.38	98.67
6	44	1	45	10		10	27.5	0.5	98.38	99.67
7	37		37	4		4	20.5	0	98.79	100.00
8	1		1			0	0.5	0	99.97	100.00
9	40		40	10		10	25	0	98.53	100.00
10	50	10	60	50		50	55	5	96.76	96.67
			0							
				Actual	Actual	Actual				
1:100 Source	15	2	17	1500	200	1700				
1:100 Source	16	1	17	1600	100	1700				
Average				1550	150	1700				

Results from Coliform Removal Studies Performed at MIT (continued):

Bacterial Removal February 18, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	25		25	11		11	18	0	99.70	100.00
2	32		32	12		12	22	0	99.64	100.00
3	65	7	72	30	4	34	53	5.5	99.13	99.48
4	38	2	40	27	1	28	34	1.5	99.44	99.86
5	147	79	226	198	81	279	252.5	80	95.86	92.38
6	57	13	70	38	2	40	55	7.5	99.10	99.29
7	6	1	7	3		3	5	0.5	99.92	99.95
8	1		1			0	0.5	0	99.99	100.00
9	250	80	330	160	70	230	280	75	95.41	92.86
10	180	90	270	370	100	470	370	95	93.93	90.95
			0							
				Actual	Actual	Actual				
1:100 Source	47	12	59	4700	1200	5900				
1:100 Source	54	9	63	5400	900	6300				
Average				5050	1050	6100				

Bacterial Removal February 22, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	13		13	5		5	9	0	99.75	100.00
2	17		17	3		3	10	0	99.72	100.00
3	71		71	14	1	15	43	0.5	98.81	99.94
4	12		12	3		3	7.5	0	99.79	100.00
5	25	11	36	30	12	42	39	11.5	98.92	98.72
6	19	1	20	14		14	17	0.5	99.53	99.94
7	14		14	8		8	11	0	99.69	100.00
8			0			0	0	0	100.00	100.00
9	100	20	120	90	20	110	115	20	96.81	97.78
10	150	10	160	110	10	120	140	10	96.11	98.89
			0							
				Actual	Actual	Actual				
1:100 Source	29	10	39	2900	1000	3900				
1:100 Source	25	8	33	2500	800	3300				
Average				2700	900	3600				

Bacterial Removal February 24, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	5		5			0	2.5	0	99.82	100.00
2	6		6	2		2	4	0	99.71	100.00
3			0	8	2	10	5	1	99.64	99.29
4	17	1	18	9	1	10	14	1	98.99	99.29
5	50	13	63	36	8	44	53.5	10.5	96.15	92.50
6	31		31	15		15	23	0	98.35	100.00
7	30		30	9		9	19.5	0	98.60	100.00
8			0			0	0	0	100.00	100.00
9	30	30	60	500	10	510	285	20	79.50	85.71
10	1050	30	1080	860	20	880	980	25	29.50	82.14
			0							
				Actual	Actual	Actual				
1:20 Source	61	4	65	1220	80	1300				
1:20 Source	64	10	74	1280	200	1480				
Average				1250	140	1390				

Results from Coliform Removal Studies Performed at MIT (continued):

Bacterial Removal February 26, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1			0			0		0		100.00
2		1	1			0		0.5		99.89
3		1	1		1	1		1		99.78
4		5	5		3	3		4		99.13
5		8	8		15	15		11.5		97.50
6		4	4		2	2		3		99.35
7		2	2			0		1		99.78
8			0			0		0		100.00
9		20	20		20	20		20		95.65
10		70	70		70	70		70		84.78
			0							
				Actual	Actual	Actual				
1:20 Source		23			460					
1:20 Source		23			460					
Average					460					

Bacterial Removal February 28, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	15		15	11		11	13	0	99.54	100.00
2	15		15	5		5	10	0	99.64	100.00
3	1		1	2		2	1.5	0	99.95	100.00
4	8		8	6		6	7	0	99.75	100.00
5	51	6	57	59	9	68	62.5	7.5	97.77	98.50
6	67	23	90	104	49	153	121.5	36	95.66	92.80
7	2	1	3	1		1	2	0.5	99.93	99.90
8			0			0	0	0	100.00	100.00
9	50		50	50	10	60	55	5	98.04	99.00
10	150	10	160	130	10	140	150	10	94.64	98.00
			0							
				Actual	Actual	Actual				
1:100 Source	25	5	30	2500	500	3000				
1:100 Source	21	5	26	2100	500	2600				
Average				2300	500	2800				

Bacterial Removal March 7, 2005

	Red Colony A	E. coli A	Total Coliform A	Red Colony B	E. coli B	Total Coliform B	Avg. TC	Avg. E. coli	% TC removed	% EC removed
1	7		7	4		4	5.5	0	99.86	100.00
2	7		7	8		8	7.5	0	99.81	100.00
3	94	11	105	32	2	34	69.5	6.5	98.24	98.82
4	11	1	12	8		8	10	0.5	99.75	99.91
5	97	34	131	106	43	149	140	38.5	96.46	93.00
6	54	13	67	26	4	30	48.5	8.5	98.77	98.45
7	2	1	3	2	2	4	3.5	1.5	99.91	99.73
8	1	1	2	2		2	2	0.5	99.95	99.91
9	80	10	90	170		170	130	5	96.71	99.09
10	60	40	100	100	50	150	125	45	96.84	91.82
			0							
				Actual	Actual	Actual				
1:100 Source	30	5	30	3000	500	3500				
1:100 Source	38	6	26	3800	600	4400				
Average				3400	550	3950				